EVALUATION OF DATA ON THE EFFECTS OF HYDRAULIC CHARACTERISTICS AND EFFLUENT CHLORINATION ON THE INCIDENCE OF MICRO-ORGANISMS OF PUBLIC HEALTH SIGNIFICANCE IN RECEIVING WATERS

TECHNICAL REPORT

Prepared for

The Ontario Ministry of the Environment
Toronto, Ontario

by

Gore & Storrie Limited
1670 Bayview Avenue
Toronto, Ontario
M4G 3C2

April 1988

EVALUATION OF DATA ON THE EFFECTS OF HYDRAULIC CHARACTERISTICS AND EFFLUENT CHLORINATION ON THE INCIDENCE OF MICRO-ORGANISMS OF PUBLIC HEALTH SIGNIFICANCE IN RECEIVING WATERS

TECHNICAL REPORT

Prepared for

The Ontario Ministry of the Environment
Toronto, Ontario

by

Gore & Storrie Limited
1670 Bayview Avenue
Toronto, Ontario
M4G 3C2

April 1988

DISCLAIMER

The views and ideas expressed in this report are those of the authors and do not necessarily reflect the views and policies of the Ministry of the Environment, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ACKNOWLEDGEMENTS

The project was financially supported by the Research Co-ordination Office, Ontario Ministry of the Environment, Toronto.

Thanks are due to Messrs. Tony Ho and Steve Klose, Water Resources Branch, for providing constructive comments and suggestions during the course of this study.

EXECUTIVE SUMMARY

Bacteriological impact of treated municipal effluent discharges to natural water bodies was analyzed. The studies utilized data gathered for the Ontario Ministry of the Environment by BEAK Consultants Limited during 1979-80 at the following sites:

- Thames River at Ingersoll
- Grand River at Grand Valley
- Otonabee River at Peterborough
- Lake Ontario at Port Hope

The review of raw data and the analyses focussed on three objectives: (1) selection of mathematical models and evaluation of their applicability; (2) determination of travel times in receiving waters at which the total and fecal coliform (TC and FC) densities are reduced to 1000/100 mL and 100/100 mL, respectively, for both chlorination and nonchlorination periods; and (3) establishing probabilistic distributions of pathogenic bacterial densities when (a) TC density range is 100 to 1000/100 mL or FC density range is 100 to 1000/100 mL.

The state-of-the-art models suitable for the studies were reviewed in conjunction with the available data. The plug flow model was selected to be suitable for each river site. The available data for the lake site were found to have large fluctuations and/or insufficient information, and hence, the data were not analysed.

The predictions of plug flow model for each sampling day at various sites were found to be closer to the observations at the corresponding sites in most cases (within a factor of one-half log cycle).

The travel times at which the TC and FC densities reach 1000/100 mL and 100/100 mL, were found to be smaller for the case of disinfected effluent discharges compared to the nondisinfected discharge cases. A sensitivity analysis indicated that the background coliform densities could significantly affect the travel times.

The correlations between the pathogenic and indicator bacteria were found to be very poor for the Grand and Thames River sites. The Otonabee River data showed correlations between: (a) *Klebsiella* and TC; (b) *P.aeruginosa* and FC; and (c) *Klebsiella* and FC.

SOMMAIRE

On a analysé l'incidence bactériologique des effluents urbains sur les plans d'eaux naturels. Pour cette étude, on a utilisé des données recueillies de 1979 à 1980 par BEAK Consultants Limited pour le ministère de l'Environnement de l'Ontario aux endroits suivants :

* la rivière Thames à Ingersoll
* la rivière Grand à Grand Valley
* la rivière Otonabee à Peterborough
* le lac Ontario à Port Hope

L'étude des données brutes et les analyses avaient trois objectifs : 1) choisir des modèles mathématiques et évaluer leur applicabilité; 2) déterminer le temps de séjour dans les eaux réceptrices pour que la concentration totale de coliformes soit ramenée à 1000 organismes/100 mL et la concentration des coliformes fécaux à 100 organismes/100 mL, tant durant les périodes de chloration que de non chloration; 3) calculer les probabilités relatives aux concentrations de bactéries pathogènes lorsque la concentration totale des coliformes varie entre 100 et 1000 organismes/100 mL et celle des coliformes fécaux varie entre 100 et 1000 organismes/100 mL.

On a passé en revue, à l'aide des données recueillies, les modèles les plus perfectionnés qui pourraient être utilisés pour ces analyses. On a finalement retenu le modèle d'écoulement à bouchons, car il s'adaptait à chacune des stations de prélèvement des rivières. On n'a pas analysé les données sur le lac car elles fluctuaient trop ou ne fournissaient pas suffisamment de renseignements.

Les projections calculées à l'aide du modèle d'écoulement à bouchons pour chaque échantillon prélevé à divers endroits se rapprochaient, dans la plupart des cas, des données recueillies aux mêmes endroits (à un facteur d'une demi-progression logarithmique près).

On a constaté que le temps de séjour nécessaire pour que la concentration totale des coliformes et celle des coliformes fécaux soient ramenées à un seuil acceptable est plus court dans le cas des effluents désinfectés que dans celui des effluents non désinfectés. Les résultats de l'analyse de sensibilité indiquent que la concentration de fond de coliformes peut influencer de façon sensible la durée du temps de séjour.

La corrélation entre les bactéries pathogènes et les bactéries témoins était pratiquement nulle dans le cas des rivières Grand et Thames. Par contre, dans la rivière Otonabee on a relevé des corrélations entre a) *Klebsiella* et la densité totale de coliformes; b) *P. aeruginosa* et les coliformes fécaux; c) *Klebsiella* et les coliformes fécaux.

CONTENTS

LIST OF FIGURES AND TABLES

1.0 INTRODUCTION

1.1 Background

A study for assessing the bacteriological impact of sewage effluent discharges to receiving waters was undertaken by the Ontario Ministry of the Environment. The overall objectives of the study were as follows (BEAK, 1982):

1. To determine if sewage effluents significantly contribute pathogenic bacteria and indicator bacteria to their receiving streams, during periods with sewage chlorination, and without;

2. To investigate the effects of natural assimilative capacity and hydraulic characteristics of the receiving waters on the growth and/or death rates of selected micro-organisms of public health importance;

3. To determine the relationship between the incidence of pathogenic bacteria and indicator bacteria in sewage effluents and in receiving waters, both with sewage chlorination and without;

4. To investigate the feasibility of using selected pathogenic bacteria as indicators of conditions hazardous to public health in effluents and receiving waters.

Detailed field studies as well as some preliminary data analyses and interpretations were carried out by BEAK Consultants Limited during 1979-82. The BEAK studies emphasized field data gathering for meeting the above objectives. The receiving water and Water Pollution Control Plant (WPCP) sites included in the studies were as follows:

- Thames River - Ingersoll WPCP
- Grand River - Grand Valley WPCP
- Otonabee River - Peterborough WPCP
- Lake Ontario - Port Hope WPCP

Figures 1 to 4, reproduced from the BEAK Report (1982), show the four study areas. All four WPCPs utilize conventional activated sludge treatment and chemical addition for nutrient reduction.

The data gathered in the BEAK study included bacteriological, chemical, hydraulic, hydrologic and meteorological characteristics from each of the four sites located in southern Ontario. The final technical report prepared by BEAK Consultants Limited included the raw data collected in the study. The analyses which utilized somewhat simpler methods, were limited to a portion of the data gathered. The Executive Summary presented in the BEAK report is included as Appendix herein. A review of the BEAK report is presented in the next chapter (Section 2.3).

1.2 Objectives of the Study

Gore & Storrie were retained by the Ontario Ministry of the Environment to carry out a follow-up study to analyze all pertinent data with well verified mathematical methods. The objectives of this follow-up study are as follows:

1. To select mathematical models applicable to the study sites by giving due consideration to the dominant processes affecting bacterial transport (eg. advection, bacterial decay/regrowth, longitudinal and lateral dispersion); and to test the applicability of the selected models through comparisons of predictions with the BEAK study field data for each site.

2. To apply the selected models for determining the longitudinal and lateral distances (or travel times) with respect to the WPCP outfalls at which the total and fecal coliform densities are reduced to 1000/100 mL and 100/100 mL, respectively, for both chlorine disinfection and no-disinfection periods. The influence of seasonal change, receiving stream hydrological conditions and background bacterial concentrations are to be incorporated in this evaluation.

3. To establish the probabilistic distributions of pathogenic bacteria concentrations in receiving streams when:

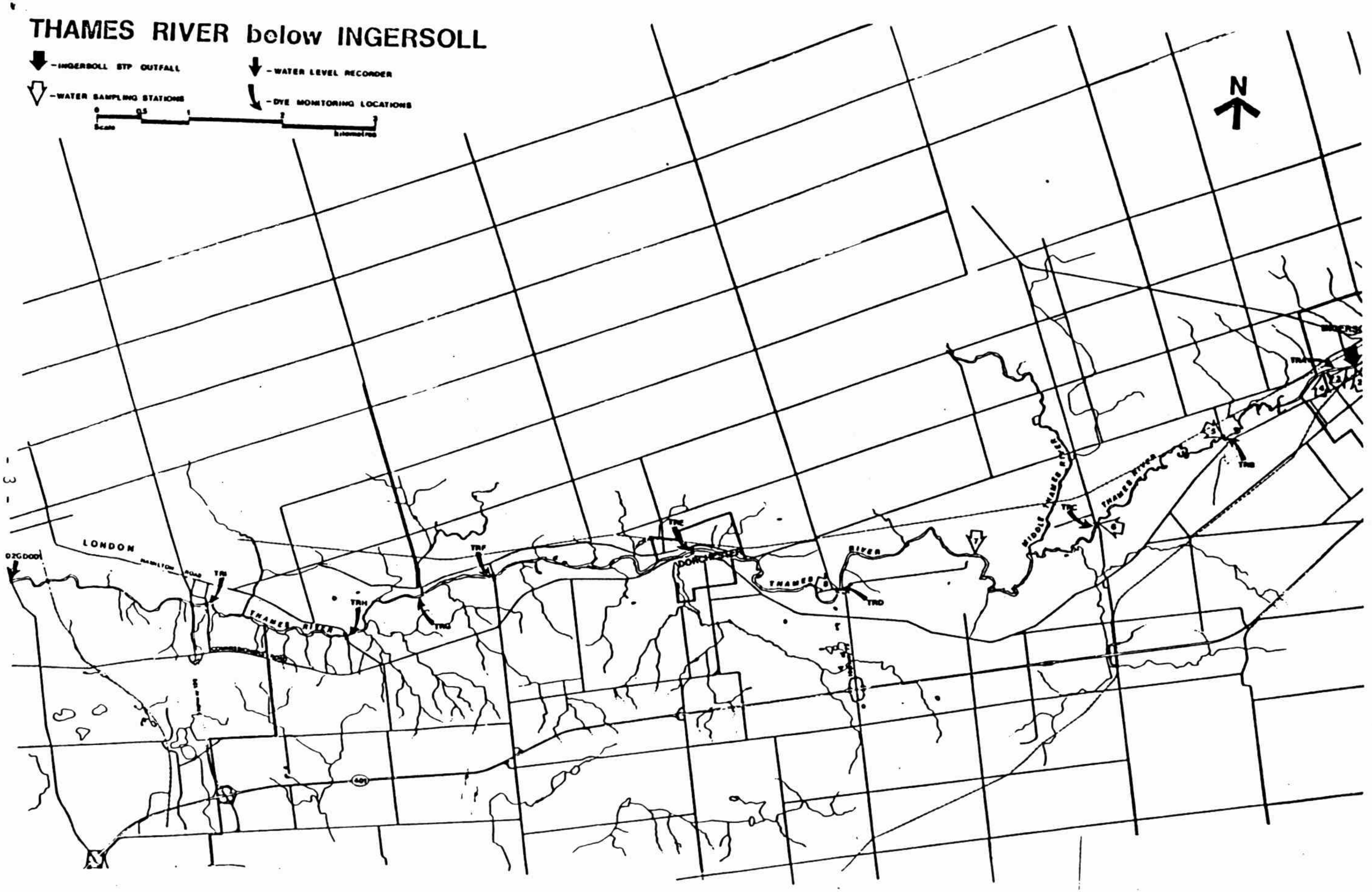


Figure 1 : Thames River Study Area

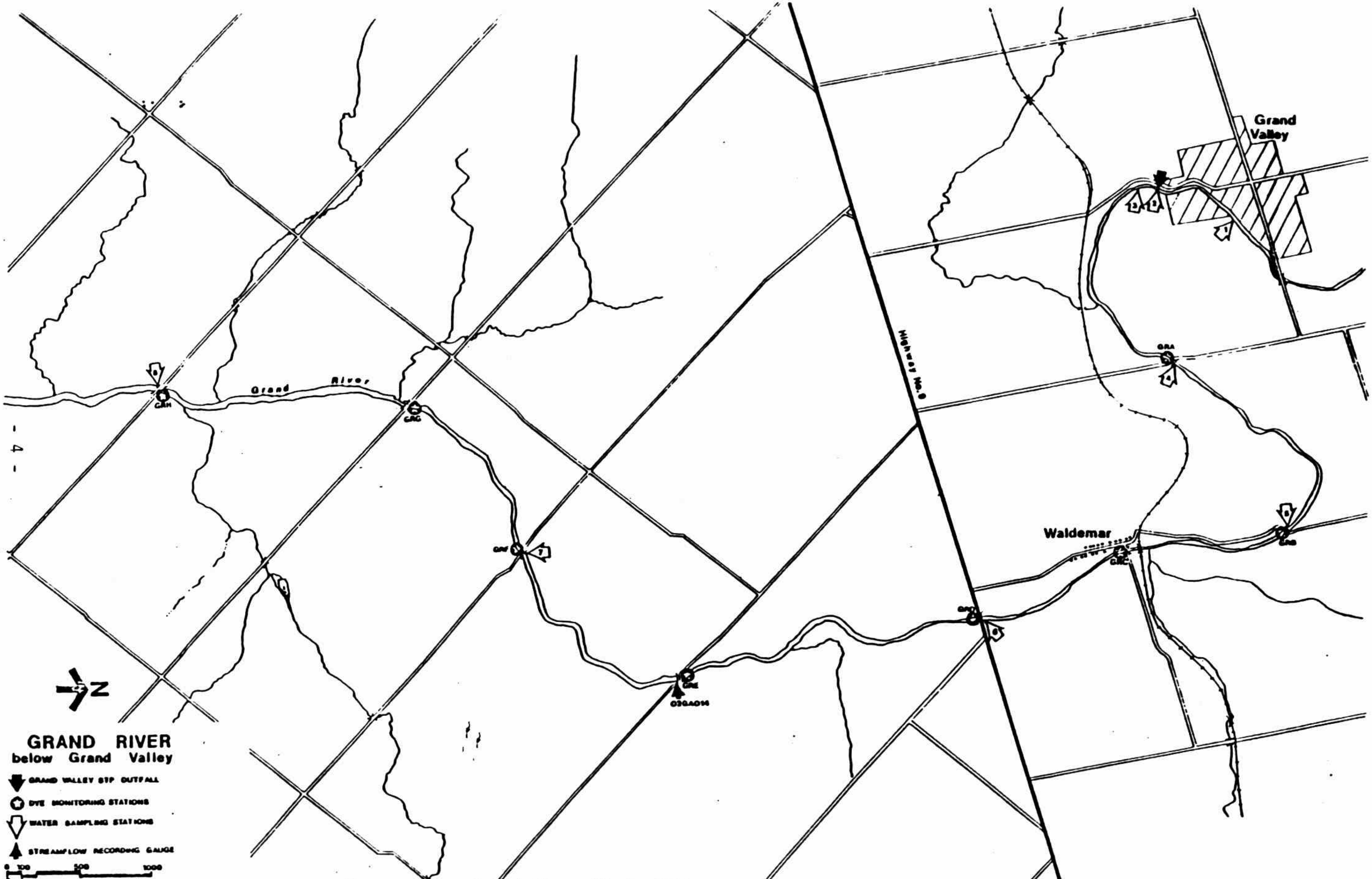


Figure 2: Grand River Study Area

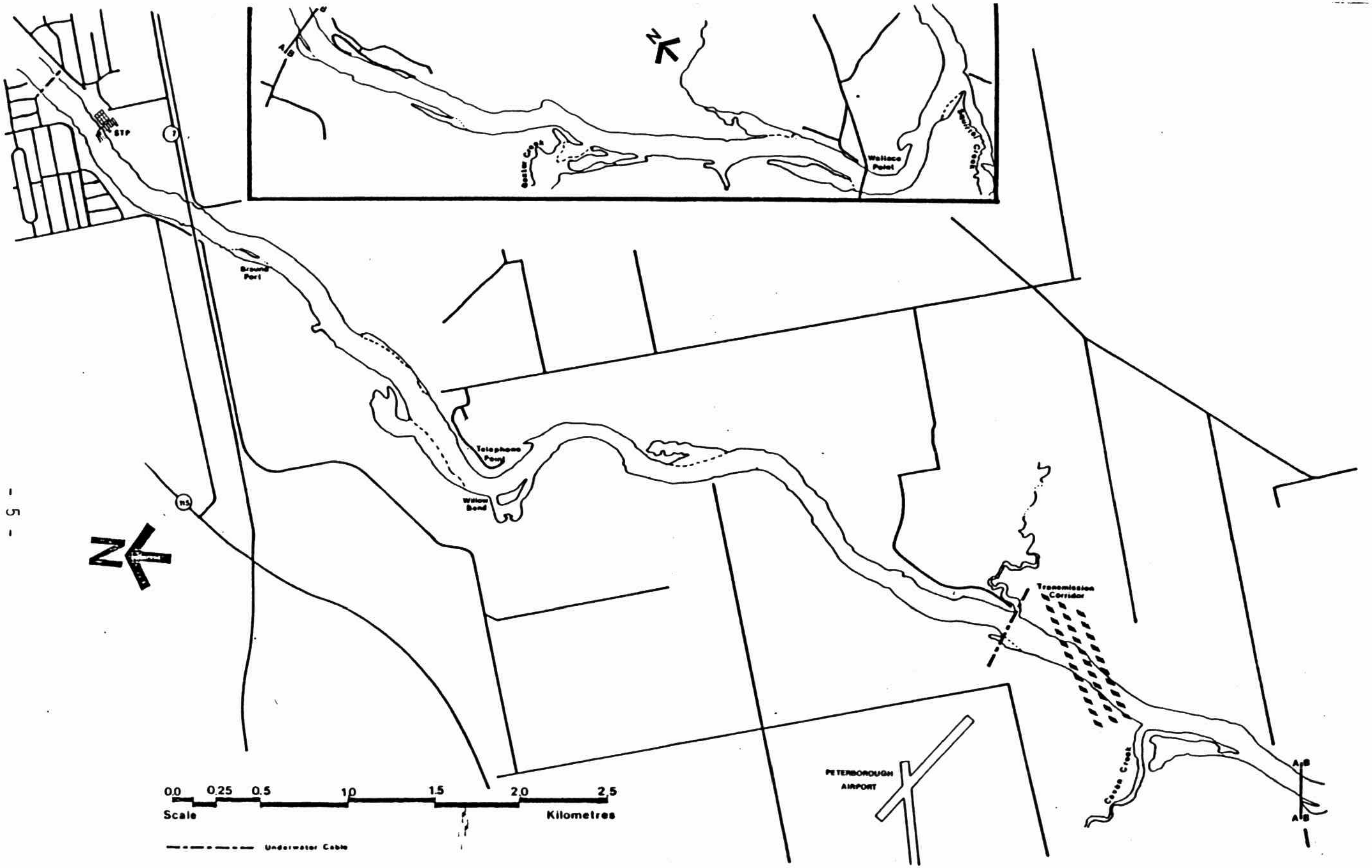
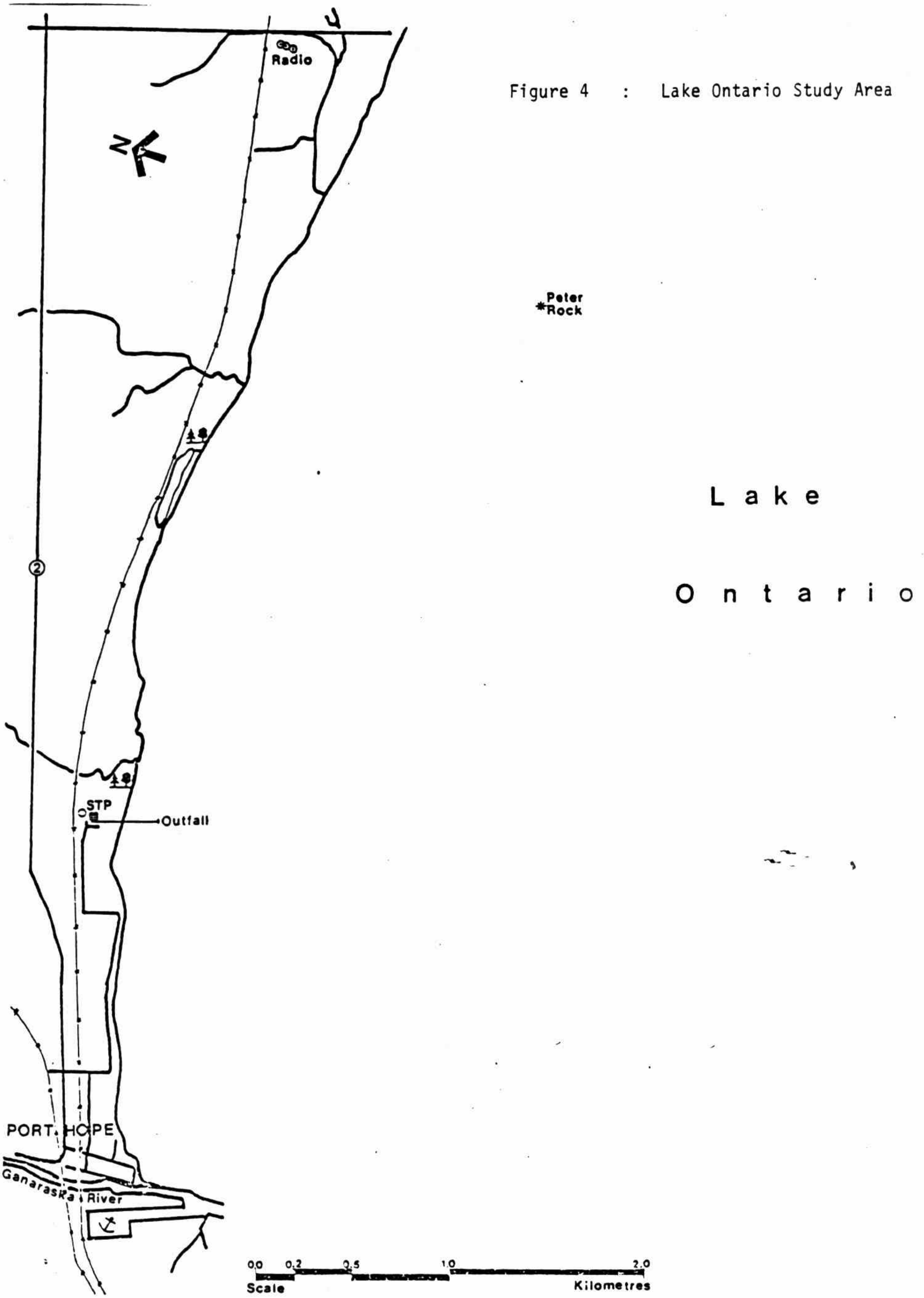


Figure 3 : Otonabee River Study Area

Figure 4 : Lake Ontario Study Area



(a) Total coliform concentrations in the same water were between 100 to 1000/100 mL or fecal coliform concentrations were between 10 to 100/100 mL;

(b) Total coliform concentrations were between 1000 to 10,000/100 mL or fecal coliform concentrations between 100 to 1000/100 mL.

2.0 WATER QUALITY COMPLIANCE ZONES

2.1 General Approach

The selection and application of mathematical methods for the first two objectives are dependent on a number of factors. These include: (1) the ability of the models to simulate the dominant processes affecting bacterial transport in the receiving waters; (2) availability of data to determine the process parameters for the suitable models; (3) the desired level of accuracy; and (4) time-frame and other resource constraints.

In this chapter, the mathematical models suitable for objectives 1 and 2 are outlined first by giving due consideration to the above-mentioned factors and the overall scope of the study. This is followed by a review of the BEAK technical report and the raw data presented therein. Data not suitable for analysis because of limitations such as incompleteness, significant variability, and time and resource constraints are also identified. Then, the mathematical method applicable to each study site is outlined. The predictions are compared to the data collected by BEAK for each site. Finally, the predicted travel times at which the bacterial objectives are met, have been presented.

2.2 Description of Mathematical Methods

2.2.1 General Factors

The boundaries of bacteriological water quality compliance zones in the far field regions of rivers and lake are dependent on the outfall characteristics, mixing of effluent in the receiving water, bacterial decay and regrowth processes, and steady/unsteady nature of the system. The models applicable to river and lake sites for defining water quality compliance zones are presented in the following subsections. These models are applicable to steady state conditions. Because of limitations imposed by time and resource constraints and data availability, models for unsteady state conditions are not considered here.

2.2.2 Models for River Sites

All the three river sites studied by BEAK involved continuous discharge of effluents. However, the analyses presented by BEAK (1982) utilized the instantaneous discharges in an attempt to relate the effluent bacterial discharges to the observed instream bacterial data. Therefore, models applicable to both instantaneous and continuous discharge conditions are described herein.

2.2.2.1 Plug Flow Model - Continuous Discharge

If instantaneous complete mixing of effluent with the receiving water is achieved immediately below the outfall, then the 1-D plug flow model with first-order decay is applicable. This method has been applied to the Grand River below the Brantford WPCP (Post and Gowda, 1981). The mathematical relationships are presented below:

$$C_x = C_a \exp(-K_d X/U) \tag{1}$$

$$X_s = \frac{U}{K_d} \ln (C_a/C_s) \tag{2}$$

$$t_s = X_s/U \tag{3}$$

$$C_a = \frac{C_e Q_e + C_b Q_b}{Q_e + Q_b} \tag{4}$$

where C_e, Q_e = effluent bacterial density and flow rate, respectively

C_b, Q_b = background bacterial density and flow rate, respectively, in the river channel just above the outfall

K_d = decay rate of bacteria

U = average flow velocity in the river channel

X = distance below the outfall

C_x = concentration in the river at a distance, X, below the outfall

C_s = water quality objective

X_s = distance below the outfall at which the objective C_s, is met

t_s = travel time corresponding to X_s

The temperature dependence of K_d is expressed by the van't Hoff-Arrhenius relationship:

$$K_2 = K_1 \, \theta^{T_2 - T_1} \qquad (5)$$

where K_1 and K_2 are the decay rates at T_1°C and T_2°C, respectively; and θ is the temperature correction factor. The streamflow dependence of U is given by the Leopold-Maddock relation:

$$U_2 = U_1 \, (Q_2/Q_1)^{u'} \qquad (6)$$

2.2.2.2 Two-Dimensional Model - Continuous Discharge

If there are lateral concentration gradients in the far field region of the receiving stream, then a 2-D model that includes transport due to lateral dispersion and first-order decay should be utilized. The models applicable to such situations are described elsewhere (Gowda, 1980, 1984a and 1984b; Post & Gowda, 1981; Smith, et al, 1983; Putz, et al, 1984; Gowda & Post, 1984). The 2-D models developed from closed form analytical solutions are simpler to use. The models include MIXCALBN and MIXAPPLN for the case of pipe outfalls, and MIXCADIF for diffuser outfall discharges. The MIXCALBN and MIXCADIF models have been calibrated and verified using field data from rivers in Ontario (Gowda, 1980 and 1984b). The MIXCALBN and MIXAPPLN models are documented in a MOE publication (Gowda, 1980). The MIXCADIF model is quite similar to MIXCALBN with minor changes in input parameters.

2.2.2.3 Models for Instantaneous and Finite-Time Discharges

The mathematical methods applicable to these cases need to consider the advection and dispersion (longitudinal and/or lateral), and

decay. Mathematical models for instantaneous and finite-time release cases are available (Gore & Storrie Ltd., 1984; 1985). However, the data presented in the BEAK report are not sufficient for such modelling studies. Therefore, these models are not considered further in this study.

2.2.3 Models for Lake Site

Mathematical models for coastal regions of lakes must account for transport due to longitudinal and lateral velocities and dispersion, as well as bacterial decay rates. Some of the models utilized by the MOE are described by Hamdy (1981) and Kohli (1981).

2.3 Review of BEAK Report and Raw Data

The executive summary of the BEAK report (1982) is presented in Appendix. A review of the BEAK report, and the raw data presented therein, was carried out with particular emphasis on the objectives of the present study (outlined in Section 1.2) and the possible mathematical methods described in the previous section. The salient aspects of the review are presented below:

- The streamflow rates for the cross-sectional survey conditions at the river sites are not stated in the BEAK report. This lack of information makes it difficult to adjust the channel cross-sectional data for the bacterial survey conditions for the river sites.

- Mixing zone study results for the study sites are presented graphically in plan view (as per cent concentration). Selected mixing zone delineation results, reproduced from the BEAK report (1982), are presented in Figures 5 to 8 for the three river sites and the lake site. These results show the existence of lateral concentration gradients in the receiving waters. However, the cross-sectional dye distribution data are not readily available and hence, the dye data cannot be utilized to determine dispersion characteristics and for model validation studies.

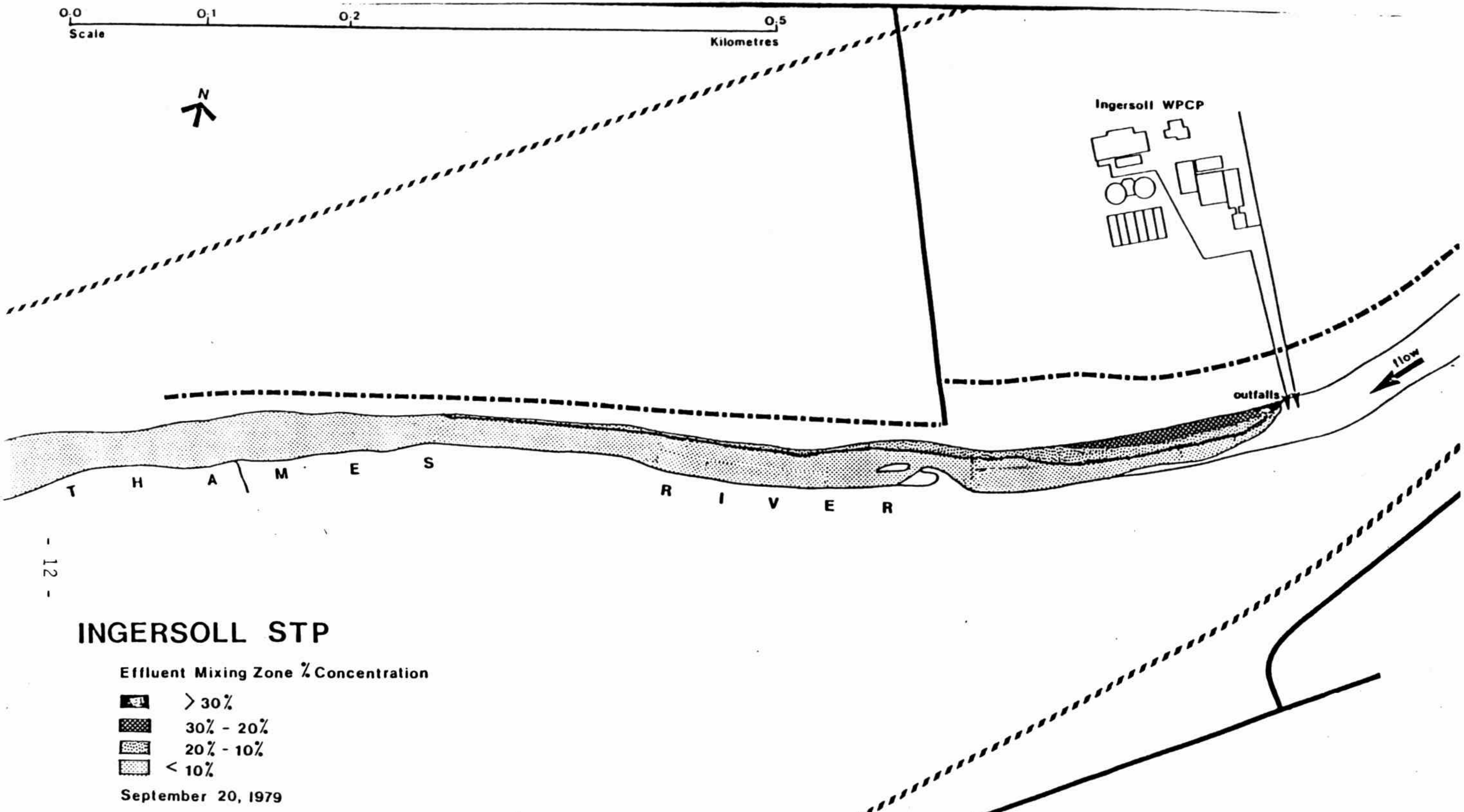


Figure 5 :   Thames River - Mixing Zone Study

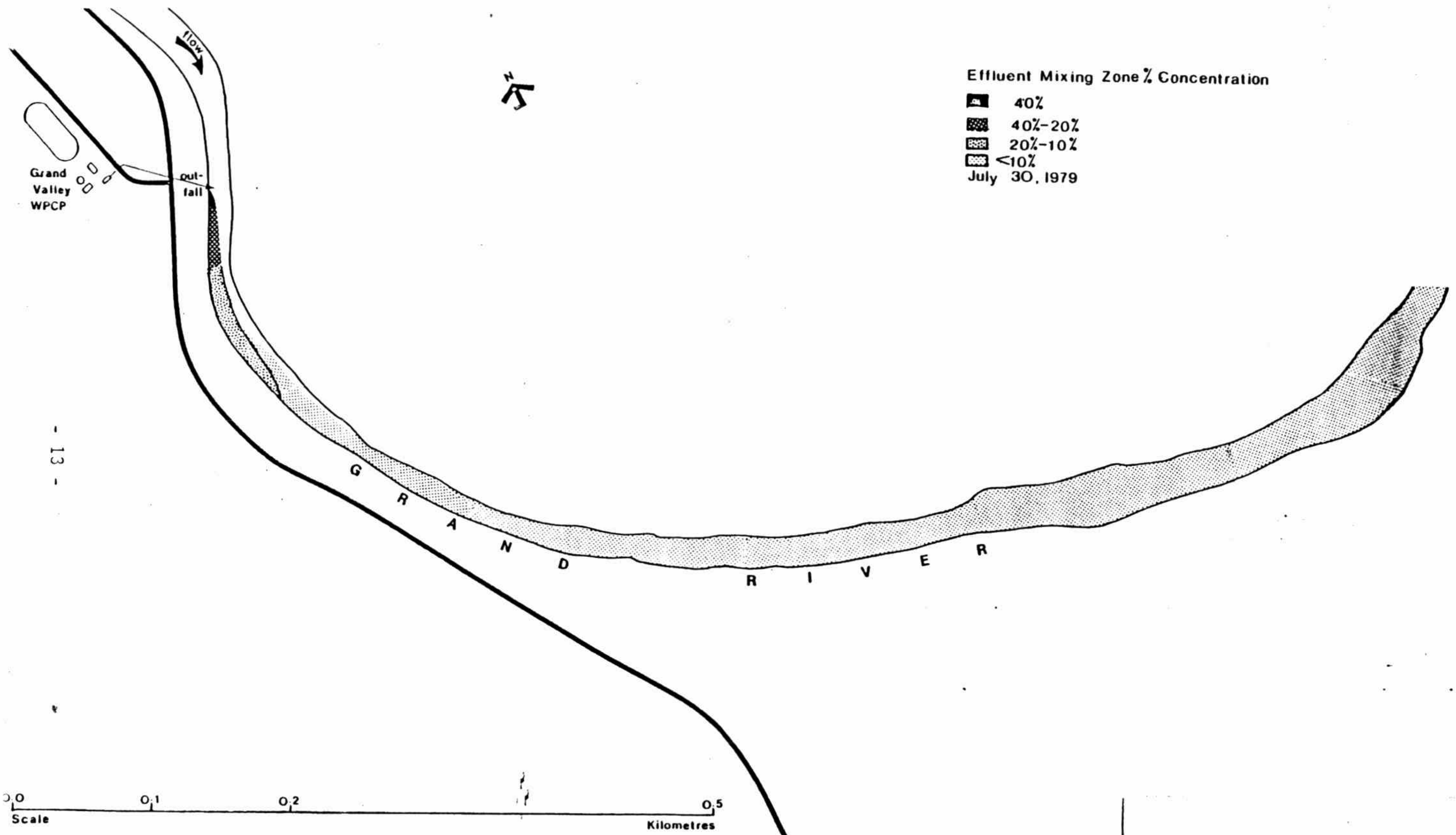


Figure 6 : Grand River - Mixing Zone Study

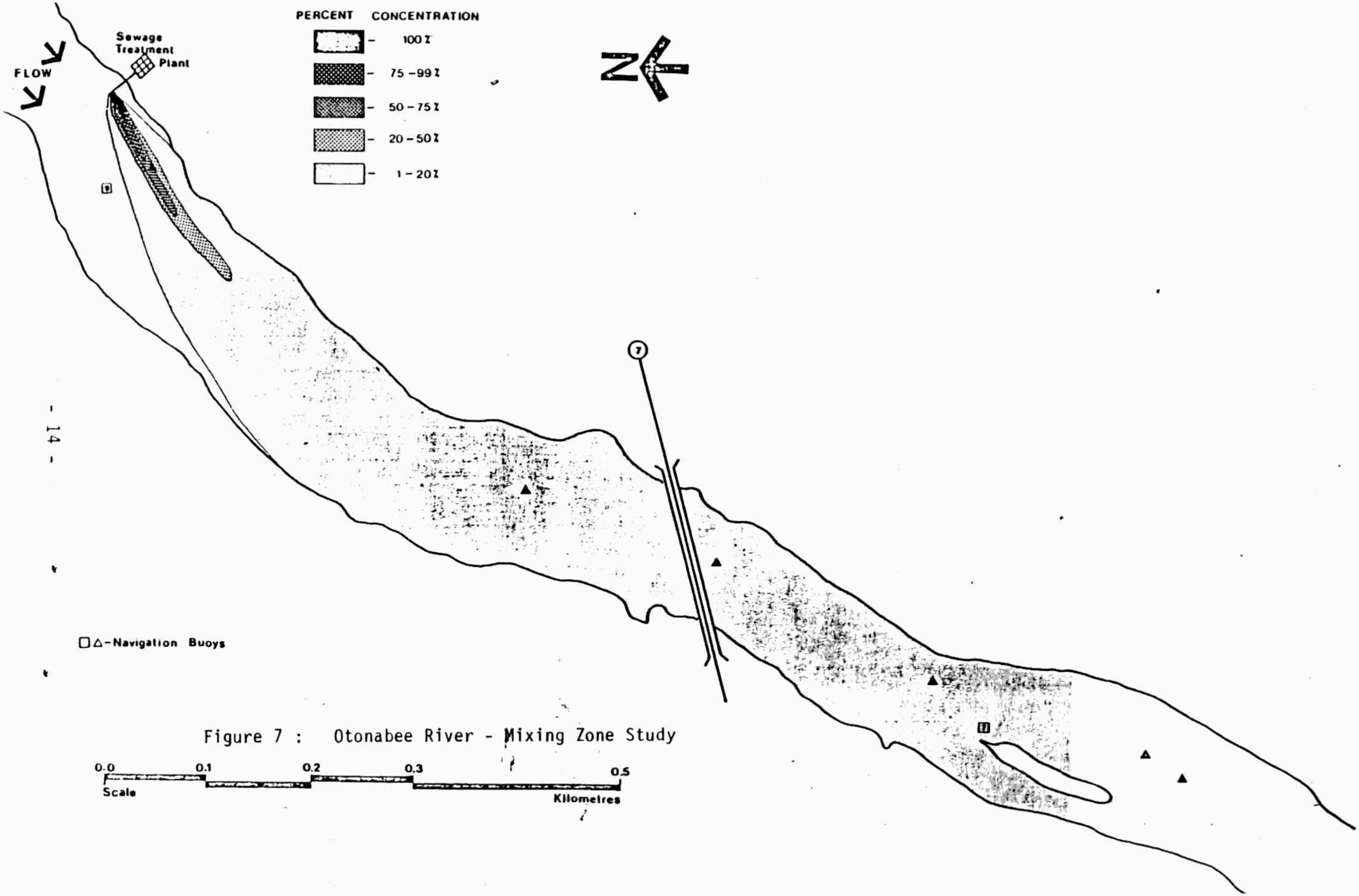


Figure 7 : Otonabee River - Mixing Zone Study

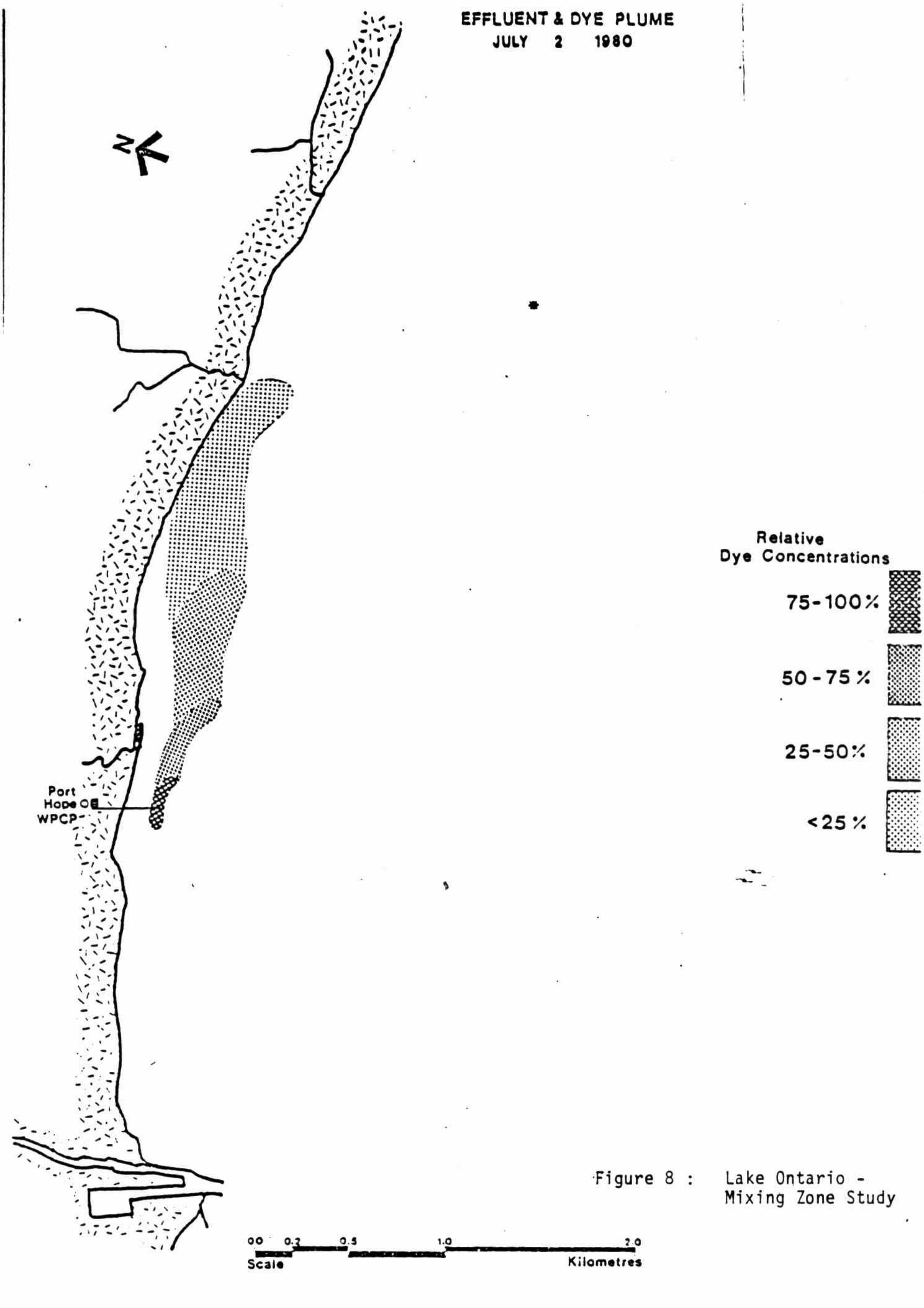


Figure 8 : Lake Ontario - Mixing Zone Study

- The mixing zone delineation results in the three river studies were not utilized to establish cross-sectional sampling points with respect to a reference bank at various stations. Therefore, the cross-sectional bacterial and chemical sampling data have some limitations for quantitative analyses, particularly where lateral variations are significant. However, for situations where the lateral variabilities are not significant, the bacterial data are useful for analysis using the plug flow model.

- In the Otonabee River study, the cross-sectional sampling locations are described as "inside the plume", "centre of plume", etc. The lack of data on the sampling locations in the cross-section precludes the use of the 2-D model.

- The sample collection at various stations (downstream from the outfall) in the river studies was not based on "following the same plug of water." The BEAK report states that the data gathered is either not suitable or subject to limitations to determine the growth/decay rate of bacteria in various reaches of the streams because of probable fluctuations in effluent inputs. Therefore, BEAK employed a method to correct the effluent concentrations by working backwards from each river monitoring station to the outfall, based on the travel time. The BEAK analysis method assumed that: (1) longitudinal and lateral dispersion effects are negligible; (2) the background and effluent bacterial concentrations are relatively stable during a day; and (3) there exist diurnal fluctuations in bacterial mass loadings due to variations in the flow rates within a day. With these assumptions, the measured bacterial densities at various river stations and the instantaneous flow rates were utilized to back-calculate the effluent concentrations. Since the method utilizes instantaneous loadings, longitudinal dispersion will affect the calculations. However, the relative significance of ignoring the longitudinal dispersion is unknown. The bacterial densities measured at some of the stations were affected by lateral dispersion. The accuracy of back-calculated bacterial densities for different times in a day

cannot be assessed because of a lack of observed data corresponding to those times. The back-calculated concentrations are subject to some limitations for quantitative analysis purposes because of these assumptions and limitations.

- There are limitations for the use of measured concentrations to determine growth/decay rates in various reaches of Grand and Thames Rivers, because of two facts; (i) the same plug of water was not sampled at successive stations; and (ii) lateral variabilities in mixing zones were not given due consideration. The Otonabee River study sampling measured the lateral variabilities, but did not sample the same plug. An examination of the various plots of bacterial mass versus travel times based on the "back-calculation" procedure indicates that it is extremely difficult or impossible to identify any bacterial growth/death patterns.

- The locations for the bacterial sampling data gathered at the lake site are not identified by spatial co-ordinates. Thus, the data cannot be used in modelling studies.

- The effluent and background densities of bacterial parameters were different on each sampling occasion. The variations from one day to another are quite large in some cases. Since there are only three values (sampled on three consecutive days for Cl_2-ON and Cl_2-OFF conditions), a statistical averaging of the data is considered inappropriate. Because of this, each day survey condition needs to be considered individually in applying the selected mathematical methods.

- Data on radiation, temperature, sediment characteristics, hydraulic parameters and inorganic water quality parameters, presented in the BEAK technical report, will be useful for examining various factors affecting the bacterial densities in the receiving waters. However, this assessment will be mostly qualitative in nature rather than quantitative due to limitations of available data and the selected mathematical methodology.

- Effluent flow rates for the study periods are not presented in the BEAK report. These data will be gathered from pertinent sources.

2.4 Mathematical Methods for Each Site

2.4.1 Thames River at Ingersoll

- September 1979 Surveys:

Mixing zone delineation study results (streamflow ≃ 1.75 m^3/s) indicate the existence of lateral concentration gradients for about 1 km below the outfall discharge. But the gradients seem to be fairly small, confined to a very narrow region near the discharge shoreline (see Figure 5). Streamflows were fairly steady during both the Cl_2-ON and Cl_2-OFF studies (1.7 - 1.8 m^3/s). However, the effluent and bacterial densities differed on each sampling day. Instantaneous complete mixing assumption appears reasonable for this condition. Therefore, the plug flow model will be utilized for the first two objectives. The analyses will take account of the background densities of total and fecal coliform bacteria.

- November - December 1979 Surveys:

Streamflows were higher than the previous studies. The background and effluent densities of TC and FC were different on each sampling day. The mixing zone boundary (streamflow = 4.2 m^3/s) was somewhat larger than the earlier study (in both the lateral and longitudinal directions).

During the Cl_2-ON study, the streamflows were unsteady, dropping from 10.3 to 5.3 m^3/s during November 30 to December 2, 1979. Therefore, the data from this survey have some limitations for steady state analyses related to the first two objectives. The possibility of analyzing the data for each day of the study utilizing the plug flow model will be explored. During the Cl_2-OFF study, the river flows dropped gradually (5.4 to 4.85 m^3/s during December 10 to 12, 1979) and steady-state assumption can be made.

The data are not suitable to apply the 2-D mixing zone models which include lateral dispersion effects. The plug flow model will be utilized by considering each day of sampling separately.

- February 1980 Surveys:

  Streamflows (ice-free conditions) were fairly steady in the range 2.0 to 2.2 m^3/s, except for an increase from 2.0 to 3.2 m^3/s during the latter half of Cl_2-OFF survey, December 20 to 21, 1980. The effluent and background densities of TC and FC differed on each sampling day.

  Concentration gradients exist both in lateral and longitudinal directions. The lateral gradients, however, appear fairly small except for about 200 m below the outfall. Therefore, the complete mixing assumption appears reasonable. The plug flow model will be applied for each day of sampling.

2.4.2 Grand River at Grand Valley

- July - August 1979 Studies:

  During the mixing zone study of July 30, 1979, the streamflow was in the range 0.46 to 0.51 m^3/s. The longitudinal distance in which significant transverse concentration gradients exist was about 450 m (see Figure 6). The streamflows during the August 1979 Cl_2-ON study were 0.47 to 0.56 m^3/s, and Cl_2-OFF flows averaged 0.37 m^3/s. Therefore, analyses based on the instantaneous complete mixing assumption appear satisfactory for the August 1979 Cl_2-ON and Cl_2-OFF surveys. The upstream and effluent bacterial densities were different on each sampling day. It is proposed to apply the plug flow model for this case. The analyses will be carried out both without and with the background densities of TC and FC.

- November 1979 Studies

A mixing zone study was conducted on November 15, 1979, when the streamflow was 3.2 m^3/s. The mixing zone was found to be quite long (over 2 km), possibly due to the higher streamflow.

Cl_2-ON, November 5-7, 1979 - Affected by rain
November 19-20, 1979 - Streamflow = 3.0 - 3.7 m^3/s

Cl_2-ON, November 19-20, 1979 - Study repeated, but no data in the BEAK technical report
- Streamflow = 4.15 m^3/s

Cl_2-OFF, November 16-18, 1979 - Streamflow = 3.0 - 3.3 m^3/s

The streamflow during the November 1979 surveys were 6 to 7 times higher than the August Survey flows. The zone of transverse concentration gradients observed during the November survey cannot be ignored. The mathematical models suitable are MIXCALBN and MIXAPPLN. However, the data available in the BEAK report are insufficient to apply these models. The background and effluent bacterial densities were different on each sampling day. The plug flow model will be applied to this case as well.

The daily sampling data indicates different upstream and effluent bacterial densities on each day. It is proposed to utilize the plug flow model by considering each day separately. Cross-sectional mean bacterial densities presented by BEAK will be utilized in the modelling study.

2.4.3 <u>Otonabee River at Peterborough</u>

Peterborough WPCP effluent flow rates for the study period are not presented in the Beak report.

- June 1980 Studies

River flow fluctuated significantly during Cl-ON study. River flow increased from 28 to 38 m3/s during June 4-5; decreased from 38 to 22

m3/s during June 5-6 remained fairly steady during June 6-7, 1980. However, mixing zone study conducted at 22 m3/s indicated that fairly complete mixing was achieved at about 400 m below the outfall. Consequently, the 1-D plug flow model will be applied in this case.

During the Cl2-OFF study, June 16-18, 1980, the streamflows were fairly steady at 20-21 m3/s. In order to be consistent in data analysis, the 1-D plug flow model will be applied here even though cross-sectional bacterial data displayed possible lateral variabilities typical of mixing zones.

- September - October 1980 Studies

Mixing zone study results (obtained flow = 46 m3/s) indicated the presence of significant concentration gradients, as well as a "shifting" plume (probably due to lateral velocity effects). Ideally, bacterial data in this case should be analysed by a 2-D model that accounts for lateral and longitudinal velocities and dispersion. However, detailed dye and velocity distribution data required to run the 2-D model were not available, hence the less idea 1-D plug flow model will be applied in this case.

Streamflow rates during Cl2-ON (September 30-October 2, 1980) were in the range of 37-40 m3/s, and it was reported to have rained heavily on October 2, 1980. The cross-sectional distributions of bacterial parameters for this case indicated some variability, but not clearly typical of distributions in mixing zones.

During the Cl2-OFF study, October 14-16, streamflows were much higher at 50-53 m3/s range.

2.4.4 Lake Ontario at Port Hope

The plume bacterial densities for the Cl_2-ON study were close to the background levels. The bacterial data for the CL_2-OFF case exhibit significant variations across the plume. Since the spatial co-ordinates of the sampling points have not been identified, the data are of limited value for modelling purposes.

As stated earlier, the dye study data presented in the BEAK report also have some limitations. The BEAK report outlines other factors of concern related to analysis: (1) effect of unbounded lake conditions on horizontal dispersion resulting in various sizes and shapes of effluent plumes on different sampling days; (2) difficulties in establishing cross-plume transects due to variations in plume dispersion characteristics during ambient field conditions; (3) changes in plume or current directions resulting in the tracked plume diluting into previously released effluent; (4) effluent build-up in the nearshore zone resulting in background levels at, or above, those in the plume; and (5) cross-plume distributions were often asymmetrical.

The readily available mathematical methods for lakes (Hamdy, 1981; Kohli, 1981) cannot be applied for the lake site because of the above-mentioned limitations. Therefore, the lake study data are not considered further herein.

2.5 River Site Modelling Studies

2.5.1 Thames River - Ingersoll WPCP Studies

The daily average effluent flow rates were obtained from the plant operational records. The effluent bacterial densities measured on the survey days were gathered from the BEAK report.

The streamflow rates for the survey dates were obtained from the streamflow gauging stations located on Thames River at Ingersoll (upstream from the WPCP outfall) and Middle Thames River at Thamesford located below the WPCP. The study segment of the Thames River channel was divided into twelve reaches. The boundaries of these reaches include the sampling locations established in the BEAK studies. The streamflow values for the reaches lying between the outfall and the Middle Thames River confluence were calculated by adding the effluent and the upstream flow rates. For the reaches lying below the confluence, the Middle Thames River flow rates were added to those just above the confluence.

The average widths, depths and velocities for the reaches were estimated by utilizing the cross-sectional data presented in the BEAK report in conjunction with the corresponding flow rate values. The Leopold-Maddock equations were utilized to adjust the widths, depths and velocities for the streamflow conditions observed during the surveys. These values are somewhat approximate estimates because of the fact that the exact dates of cross-sectional surveys and corresponding streamflows are not known.

The measured bacterial densities in the river just above the Ingersoll WPCP outfall were obtained from the BEAK report. The river water temperature values observed during each survey were also obtained from the BEAK report.

The plug flow model was utilized for this site. Individual modelling runs were carried out for each day of survey conditions. The decay rates (K_d) of fecal and total coliform bacteria were assumed to be 1.0 and 1.0 per day at 20°C (base e), respectively, for each reach based on the values reported in the literature (Zison, et al, 1978). These rates were adjusted to the temperatures observed on each sampling day (using Equation 5), and then applied to both the river background and effluent bacterial loadings.

For a comparison of the observations and plug flow model predictions, a factor (R_L) has been utilized. The factor is defined by:

$$R_L = \log \frac{(X_{pred})}{(X_{obs})}$$

in which X denotes the FC or TC bacterial density; and the subscripts "pred" and "obs" refer to the predicted and observed values, respectively. A positive value of R_L indicates a predicted value greater than observation and vice versa; and $R_L = 0$ implies perfect agreement of the two values. The bacterial measurement techniques are imprecise; and hence, the predicted and observed values are considered to be in reasonable agreement when the difference is within one-half log cycle, ie. $R_L \leq \pm 0.5$.

The bacterial densities predicted by the plug flow model, as well as the measured densities for various sampling locations, are presented in Tables 1 and 2 for FC and TC, respectively. The times of travel (TOT) and R_L values are also given in the tables. The predicted and measured values are in reasonable agreement in most cases ($R_L \leq \pm 0.5$) and differ significantly only in very few cases. Generally, the discrepancies are pronounced at the first station below the outfall and on those days when the background and/or effluent densities differed by more than two log cycles. The large discrepancies at the first station may be due to incomplete mixing (but the model assumed complete mixing). In general, the differences seem to be unaffected by the seasons or travel times.

The plug flow model was utilized to determine the travel times with respect to the WPCP outfall at which the FC and TC densities are reduced to 100/100 mL and 1000/100 mL, respectively. The predicted travel times (hours) are summarized in Table 3. In general, these predictions indicate that:

1. The travel times with effluent chlorination are generally much lower than those without effluent chlorination.

2. The river background densities have a significant effect on the travel times at which the desired objectives can be attained. Therefore, if upstream bacterial contamination is significant, then effluent disinfection may have very little effect on the stream bacteriological quality downstream of discharge.

3. The travel times are marginally affected by seasonal changes.

2.5.2 Grand River - Grand Valley WPCP Studies

The effluent, as well as river flow and quality data required for the plug flow model, were obtained from the plant operational data, streamflow records and the BEAK report. The decay rates for FC and

Table 1 COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
SUMMER									
DAY1	T. TIME (hr)			0.12	1.55	9.49	16.03	19.71	23.55
CHLORINE-ON	OBSERVED	2500	7300	1700	1490	1600	1030	370	330
	PREDICTED			2623	2458	1770	1127	872	621
	LOG(PRE/OBS)			0.19	0.22	0.04	0.04	0.37	0.27
DAY 2	T. TIME (hr)			0.12	1.55	9.51	16.09	19.6	23.67
CHLORINE-ON	OBSERVED	3400	600	2100	5200	1800	890	630	3600
	PREDICTED			3308	3096	2217	1399	1077	762
	LOG(PRE/OBS)			0.2	-0.23	0.09	0.2	0.23	-0.67
DAY 3	T. TIME (hr)			0.13	1.61	9.92	16.74	20.6	24.63
CHLORINE-ON	OBSERVED	17200	100	10	4400	1640	1700	2700	10600
	PREDICTED			16647	15551	11081	6942	5317	3740
	LOG(PRE/OBS)			3.22	0.55	0.83	0.61	0.29	-0.45
DAY 4	T. TIME (hr)			0.12	1.5	9.23	13.26	15.5	22.65
CHLORINE-ON	OBSERVED	7700	6700000	1790000	240000	145000	151000	193000	133000
	PREDICTED			176265	165563	120494	78070	61006	44069
	LOG(PRE/OBS)			-1.01	-0.16	-0.08	-0.29	-0.5	-0.48
DAY 5	T. TIME (hr)			0.12	1.54	9.48	13.67	16.02	23.53
CHLORINE-OFF	OBSERVED	6600	1330000	320000	40000	16000	3000	1000	6000
	PREDICTED			41560	38952	28065	17896	13851	9881
	LOG(PRE/OBS)			-0.89	-0.01	0.24	0.78	1.14	0.22
DAY 6	T. TIME (hr)			0.12	1.5	9.21	13.24	15.47	22.61
CHLORINE-OFF	OBSERVED	600	1350000	1000000	10000	5000	1000	1000	4000
	PREDICTED			35535	33394	24360	15842	12406	8958
	LOG(PRE/OBS)			-1.45	0.52	0.69	1.2	1.09	0.35

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 1 CONTINUED ....
COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
FALL									
DAY1	T. TIME (hr)			0.07	0.33	1.9	3.92	5.55	
CHLORINE-ON	OBSERVED	570	6300	790	1050	770	490	640	410
	PREDICTED			653	647	577	526	425	
	LOG(PRE/OBS)			-0.08	-0.21	-0.13	0.03	-0.18	
DAY 2	T. TIME (hr)			0.08	0.36	2.38	4.81	6.97	
CHLORINE-ON	OBSERVED	680	5500	890	640	730	320	316	296
	PREDICTED			775	766	662	592	445	
	LOG(PRE/OBS)			-0.06	0.08	-0.04	0.27	0.15	
DAY 3	T. TIME (hr)			0.09	0.39	2.95	5.65	8.3	
CHLORINE-ON	OBSERVED	370	10000	3500	830	290	276	244	336
	PREDICTED			655	646	542	477	335	
	LOG(PRE/OBS)			-0.73	-0.16	0.27	0.24	0.14	
DAY 4	T. TIME (hr)			0.09	0.4	2.9	5.72	8.39	10.77
CHLORINE-ON	OBSERVED	450	11600	1170	420	430	450	220	240
	PREDICTED			587	583	538	500	430	375
	LOG(PRE/OBS)			-0.3	0.14	0.1	0.05	0.29	0.19
DAY 5	T. TIME (hr)			0.09	0.41	3.08	6.07	8.97	11.55
CHLORINE-OFF	OBSERVED	1000	8700	2260	740	670	430	620	430
	PREDICTED			1097	1089	1000	926	790	681
	LOG(PRE/OBS)			-0.31	0.17	0.17	0.33	0.11	0.2
DAY 6	T. TIME (hr)			0.09	0.41	3.11	6.11	9.07	11.07
CHLORINE-OFF	OBSERVED	1380	7700	1902	1870	990	580	750	360
	PREDICTED			1457	1446	1326	1227	1040	897
	LOG(PRE/OBS)			-0.12	-0.11	0.13	0.33	0.14	0.2

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 1 CONTINUED .....
COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
WINTER									
DAY1 CHLORINE-ON	T. TIME (hr)			0.07	0.33	5.1	9.71	12.89	15.72
	OBSERVED	850	4	500	420	1120	600	250	36
	PREDICTED			830	820	712	639	483	373
	LOG(PRE/OBS)			0.22	0.29	-0.2	0.03	0.29	1.02
DAY 2 CHLORINE-ON	T. TIME (hr)			0.08	0.34	5.14	9.79	13	15.86
	OBSERVED	640	0	370	540	1290	780	184	72
	PREDICTED			627	612	537	482	362	279
	LOG(PRE/OBS)			0.23	0.05	-0.38	-0.21	0.29	0.59
DAY 3 CHLORINE-ON	T. TIME (hr)			0.08	0.34	5.23	9.93	13.23	16.16
	OBSERVED	410	0	12	420	220	1010	138	24
	PREDICTED			403	398	344	308	230	177
	LOG(PRE/OBS)			1.53	-0.02	-0.09	-0.52	0.14	0.87
DAY 4 CHLORINE-ON	T. TIME (hr)			0.08	0.35	5.55	10.46	13.96	17.07
	OBSERVED	560	132000	24000	1530	700	910	400	138
	PREDICTED			3204	3161	2685	2376	1713	1265
	LOG(PRE/OBS)			-0.87	0.32	0.58	0.42	0.63	0.96
DAY 5 CHLORINE-OFF	T. TIME (hr)			0.08	0.35	5.55	10.46	13.96	17.07
	OBSERVED	570	75000	12000	1510	1350	1940	830	670
	PREDICTED			2208	2179	1851	1638	1182	873
	LOG(PRE/OBS)			-0.74	0.16	0.14	-0.07	0.15	0.11
DAY 6 CHLORINE-OFF	T. TIME (hr)			0.07	0.32	4.57	8.82	11.65	14.19
	OBSERVED	2370	51000	12100	3160	1030	1150	560	152
	PREDICTED			3220	3184	2782	2503	1921	1504
	LOG(PRE/OBS)			-0.57	0	0.43	0.34	0.54	1

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 2 COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
SUMMER									
DAY1	T. TIME (hr)			0.12	1.55	9.49	16.03	19.71	23.53
CHLORINE-ON	OBSERVED	1500	37000	34000	22000	11600	14000	23000	10000
	PREDICTED			2508	2350	1692	1078	833	594
	LOG(PRE/OBS)			-1.13	-0.97	-0.84	-1.11	-1.44	-1.23
DAY 2	T. TIME (hr)			0.12	1.55	9.57	16.09	19.8	23.67
CHLORINE-ON	OBSERVED	12100	1900	25000	70000	67000	118000	94000	212000
	PREDICTED			117214	109707	78549	49590	38154	27003
	LOG(PRE/OBS)			0.67	0.2	0.07	-0.38	-0.39	-0.89
DAY 3	T. TIME (hr)			0.13	1.61	9.92	16.74	20.6	24.63
CHLORINE-ON	OBSERVED	74000	1000	60	91000	57000	86000	68000	126000
	PREDICTED			71572	70025	47684	29874	22880	16095
	LOG(PRE/OBS)			3.08	-0.11	-0.08	-0.46	-0.47	-0.89
DAY 4	T. TIME (hr)			0.12	1.5	9.23	13.26	15.5	22.65
CHLORINE-ON	OBSERVED	48000	7600000	2600000	400000	93000	99000	178000	101000
	PREDICTED			273992	223542	162690	105410	82370	59502
	LOG(PRE/OBS)			-1.04	-0.25	0.24	0.03	-0.33	-0.23
DAY 5	T. TIME (hr)			0.12	1.54	9.48	13.67	16.02	23.53
CHLORINE-OFF	OBSERVED	65000	7300000	1490000	80000	86000	61000	53000	98000
	PREDICTED			255958	239892	172841	110214	85306	60852
	LOG(PRE/OBS)			-0.77	0.48	0.3	0.26	0.21	-0.21
DAY 6	T. TIME (hr)			0.12	1.5	9.21	13.24	15.47	22.61
CHLORINE-OFF	OBSERVED	56000	1180000	2000000	810000	3030000	210000	210000	217000
	PREDICTED			3110000	2920000	2130000	1390000	1090000	786500
	LOG(PRE/OBS)			0.19	0.56	-0.15	0.82	0.71	0.56

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 2 CONTINUED ....
COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
FALL									
DAY1 CHLORINE-ON	T. TIME (hr)			0.07	0.33	1.9	3.92	5.53	
	OBSERVED	7000	25000	7800	9300	6400	5900	7400	7000
	PREDICTED			7244	7176	6403	5836	4681	
	LOG(PRE/OBS)			-0.13	-0.11	0	0	-0.2	
DAY 2 CHLORINE-ON	T. TIME (hr)			0.08	0.36	2.38	4.81	6.97	
	OBSERVED	10800	105000	12000	5700	7600	5900	5200	5000
	PREDICTED			12664	12511	10819	9680	7258	
	LOG(PRE/OBS)			0.02	0.34	0.15	0.21	0.14	
DAY 3 CHLORINE-ON	T. TIME (hr)			0.09	0.39	2.85	5.65	8.3	
	OBSERVED	10500	27000	65000	21000	12800	7300	8100	9400
	PREDICTED			10949	10790	9053	7965	5590	
	LOG(PRE/OBS)				-0.77	-0.29	-0.15	0.04	-0.16
DAY 4 CHLORINE-ON	T. TIME (hr)			0.09	0.4	2.9	5.72	8.39	10.77
	OBSERVED	24000	164000	30000	23000	14200	14900	10900	11500
	PREDICTED			25667	25495	23518	21866	18819	16391
	LOG(PRE/OBS)			-0.07	0.04	0.22	0.17	0.24	0.15
DAY 5 CHLORINE-OFF	T. TIME (hr)			0.09	0.41	3.08	6.07	8.97	11.55
	OBSERVED	24000	77000	32000	26000	14400	12300	11100	10500
	PREDICTED			24616	24440	22431	20785	17703	15271
	LOG(PRE/OBS)			-0.11	-0.03	0.19	0.23	0.2	0.16
DAY 6 CHLORINE-OFF	T. TIME (hr)			0.09	0.41	3.11	6.11	9.07	11.07
	OBSERVED	10500	27000	65000	21000	12800	7300	8100	9400
	PREDICTED			19000	9400	10800	9900	10100	9700
	LOG(PRE/OBS)			-0.15	0.15	0.05	0.05	-0.02	-0.07

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 2 CONTINUED .....
COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR THAMES RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
WINTER									
DAY1	T. TIME (hr)			0.07	0.33	5.1	9.71	12.89	15.72
CHLORINE-ON	OBSERVED	10100	44	9000	8400	7500	7700	3300	790
	PREDICTED			9862	9747	8464	7598	5744	4431
	LOG(PRE/OBS)			0.04	0.06	0.05	-0.01	0.24	0.75
DAY 2	T. TIME (hr)			0.08	0.14	5.14	9.79	13	15.86
CHLORINE-ON	OBSERVED	7900	10	7500	10400	9400	8600	2900	870
	PREDICTED			7739	7747	6629	5945	4478	3442
	LOG(PRE/OBS)			0.01	-0.13	-0.15	-0.16	0.19	0.6
DAY 3	T. TIME (hr)			0.08	0.34	5.23	9.93	13.23	16.16
CHLORINE-ON	OBSERVED	3000	170	2130	3400	4200	5300	1170	280
	PREDICTED			2947	2911	2519	2256	1691	1294
	LOG(PRE/OBS)			0.14	-0.07	-0.22	-0.37	0.16	0.66
DAY 4	T. TIME (hr)			0.08	0.35	5.55	10.46	13.96	17.07
CHLORINE-ON	OBSERVED	1570	1630000	450000	22000	10100	15300	5300	3500
	PREDICTED			34353	33887	28780	25468	18380	13565
	LOG(PRE/OBS)			-1.12	0.19	0.45	0.22	0.54	0.59
DAY 5	T. TIME (hr)			0.08	0.35	5.55	10.46	13.96	17.07
CHLORINE-OFF	OBSERVED	2800	1180000	280000	13000	7300	6200	4900	4200
	PREDICTED			28739	28350	24038	21315	15389	11363
	LOG(PRE/OBS)			-0.99	0.34	0.52	0.54	0.5	0.43
DAY 6	T. TIME (hr)			0.07	0.32	4.57	8.82	11.65	14.18
CHLORINE-OFF	OBSERVED	6700	1040000	180000	31000	7300	6200	4300	1500
	PREDICTED			24921	24645	12568	19423	14954	11735
	LOG(PRE/OBS)			-0.86	-0.1	0.47	0.5	0.54	0.89

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

TABLE 3
SUMMARY OF PREDICTED TRAVEL TIMES WHERE BACTERIAL OBJECTIVES ARE MET – THAMES RIVER

Season & Date	Case	Travel Time (hrs) Where FC Objective = 100/100 mL		Travel Time (hrs) Where TC Objective = 1000/100 mL		Upstream River Discharge (m^3/s)
		Without Background	With Background	Without Background	With Background	
Summer						
Sept. 6-8, 1979	Cl_2-ON:					
	Day 1	20.08	88.43	1.72	25.00	1.75
	Day 2	0.0	94.71	0.0	128.89	1.71
	Day 3	0.0	138.35	0.0	115.56	1.67
Sept. 19-21, 1979	Cl_2-OFF:					
	Day 4	200.96	202.13	142.15	148.03	1.85
	Day 5	158.58	163.09	142.37	149.99	1.76
	Day 6	158.41	158.86	216.99	217.47	1.87
Fall						
Nov. 30 – Dec 2, 1979	Cl_2-ON:					
	Day 1	0.00	76.85	0.0	81.07	3.05
	Day 2	4.46	83.84	30.89	103.92	2.15
	Day 3	44.74	76.99	0.00	97.98	1.63
Dec. 10-12, 1979	Cl_2-OFF:					
	Day 4	14.16	68.30	27.50	125.14	5.41
	Day 5	4.84	92.40	0.14	123.53	4.96
	Day 6	0.0	103.32	1.09	99.89	4.86
Winter						
Feb. 7-9, 1980	Cl_2-ON:					
	Day 1	0.0	89.24	0.0	96.50	2.15
	Day 2	0.0	77.44	0.0	86.30	2.12
	Day 3	0.0	58.78	0.0	45.65	2.08
Feb. 19-21, 1981	Cl_2-OFF:					
	Day 4	130.32	137.74	138.69	140.50	1.90
	Day 5	111.48	122.97	129.46	133.42	1.90
	Day 6	87.36	137.92	115.63	127.75	2.50

TC bacteria were the same as for the Thames River studies (ie. 1.0 and 1.0 per day) and were adjusted to the temperatures observed in the Grand River.

The observed and predicted FC and TC densities for various sampling runs are summarized in Tables 4 and 5, respectively, As in the Thames River case, the predictions compare fairly well for sampling runs and differ significantly for very limited runs. The differences between the observations and predictions are seen to be quite significant for the days when the upstream densities are considerably different from the other sampling days. The large difference between observed and predicted values (e.g. differences in TC densities in Table 5, on Day 6 in the summer period) may be caused by sampling or analytical error in measuring TC density in the background water. This surmize however, cannot be confirmed.

The travel times at which the FC and TC densities are reduced to the guideline values of 100/100 mL and 1000/100 mL, respectively, are presented in Table 6. These predictions by the plug flow model are seen to be lower with effluent chlorination compared to the non-chlorination runs. The observed changes in background densities from one day to another are seen to affect the travel time values. The findings herein are somewhat similar to the Thames River results.

2.5.3 Otonabee River - Peterborough WPCP Studies

The WPCP effluent quality and flow rates, as well as the Otonabee River characteristics, were determined from various sources as for the Thames and Grand River studies. The bacterial decay rates were also the same as in the other river studies, scaled up to the average river temperatures for each sampling day.

The FC and TC densities predicted by the plug flow model for the Otonabee River sampling sites are presented in Tables 7 and 8, respectively, along with the corresponding observed values. The predictions are closer to the observations for some sampling runs, but differ in others, as for the other two river study sites. The observed background densities on different sampling dates are seen to affect the comparative results at this river site as well.

TABLE 4 COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR GRAND RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
				MONITORING STATIONS					
SUMMER									
DAY1	T. TIME (hr)			0.25	4.59	7.65	13.58	16.03	18.09
CHLORINE-ON	OBSERVED	350	130	349	349	349	349	349	349
	PREDICTED			347	346	340	310	296	250
	LOG(PRE/OBS)			0	0	-0.01	-0.05	-0.07	-0.14
DAY 2	T. TIME (hr)			0.26	4.74	7.9	14.46	17.22	20.29
CHLORINE-ON	OBSERVED	300	20	299	299	299	298	298	298
	PREDICTED			297	296	291	265	251	211
	LOG(PRE/OBS)			0	0	-0.01	-0.05	-0.07	-0.15
DAY 3	T. TIME (hr)			0.27	4.95	8.24	15.88	19.18	22.61
CHLORINE-ON	OBSERVED	90	8	89	90	90	90	89	89
	PREDICTED			89	89	87	78	74	61
	LOG(PRE/OBS)			0	0	-0.01	-0.06	-0.08	-0.16
DAY 4	T. TIME (hr)			0.23	4.18	6.97	11.4	13.11	12.45
CHLORINE-ON	OBSERVED	680	86000	1127	833	816	963	962	1088
	PREDICTED			928	926	911	843	810	702
	LOG(PRE/OBS)			-0.19	-0.07	-0.06	0.05	0.05	-0.08
DAY 5	T. TIME (hr)			0.24	4.26	7.1	11.38	13.77	16.25
CHLORINE-OFF	OBSERVED	510	104000	1039	893	691	885	883	1055
	PREDICTED			853	851	837	771	738	635
	LOG(PRE/OBS)			-0.09	-0.02	0.08	-0.06	-0.04	-0.22
DAY 6	T. TIME (hr)			0.23	4.13	6.88	11.13	12.76	15.06
CHLORINE-OFF	OBSERVED	360	129000	1261	818	579	829	1076	1308
	PREDICTED			718	716	704	653	627	544
	LOG(PRE/OBS)			-0.24	-0.06	0.08	-0.1	-0.2	-0.38

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG (PREDICTED/OBSERVED)

TABLE 4 CONTINUED ....

COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR GRAND RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
FALL									
DAY1 CHLORINE-ON	T. TIME (hr)			0.12	4.22	4.8	7.35	9.95	12.02
	OBSERVED	90	10	90	90	90	90	90	90
	PREDICTED			88	87	85	73	67	62
	LOG(PRE/OBS)			0	-0.01	-0.02	-0.09	-0.12	-0.16
DAY 2 CHLORINE-ON	T. TIME (hr)			0.13	4.56	5.31	8.1	11.09	13.47
	OBSERVED	72	15400	104	84	84	84	90	89
	PREDICTED			81	80	78	66	60	55
	LOG(PRE/OBS)			-0.11	-0.02	-0.03	-0.1	-0.17	-0.21
DAY 3 CHLORINE-ON	T. TIME (hr)			0.13	4.61	5.38	8.19	11.12	13.62
	OBSERVED	256	152	256	256	256	256	256	256
	PREDICTED			250	246	242	202	185	169
	LOG(PRE/OBS)			-0.01	-0.02	-0.02	-0.1	-0.14	-0.18
DAY 4 CHLORINE-ON	T. TIME (hr)			0.13	4.55	5.27	8.02	10.95	13.27
	OBSERVED	940	8000	949	952	952	949	948	949
	PREDICTED			924	909	893	748	687	630
	LOG(PRE/OBS)			-0.01	-0.02	-0.03	-0.1	-0.14	-0.18
DAY 5 CHLORINE-OFF	T. TIME (hr)			0.13	4.56	5.32	8.11	11.1	13.48
	OBSERVED	16	124000	227	66	66	121	120	169
	PREDICTED			107	105	103	86	79	72
	LOG(PRE/OBS)			-0.32	0.21	0.2	-0.14	-0.18	-0.37
DAY 6 CHLORINE-OFF	T. TIME (hr)			0.13	4.46	5.14	7.82	10.65	12.9
	OBSERVED	108	63000	158	158	158	159	159	187
	PREDICTED			152	150	147	124	114	105
	LOG(PRE/OBS)			-0.01	-0.02	-0.03	-0.11	-0.14	-0.25

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 5 COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR GRAND RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
SUMMER									
DAY1	T. TIME (hr)			0.25	4.59	7.65	13.58	16.03	18.09
CHLORINE-ON	OBSERVED	13000	1800	27000	18000	14400	15600	13100	13500
	PREDICTED			12800	12841	12611	11517	10970	9269
	LOG(PRE/OBS)			-0.32	-0.15	-0.06	-0.13	-0.08	-0.16
DAY 2	T. TIME (hr)			0.26	4.74	7.9	14.46	17.22	20.29
CHLORINE-ON	OBSERVED	13100	520	169000	132000	139000	140000	96000	20000
	PREDICTED			12987	12947	12708	11550	10974	9193
	LOG(PRE/OBS)			-0.11	-0.01	-0.04	-0.08	0.06	-0.34
DAY 3	T. TIME (hr)			0.27	4.95	8.24	15.88	19.18	22.61
CHLORINE-ON	OBSERVED	6800	52	11800	13300	3500	10000	7100	12400
	PREDICTED			6724	6702	6570	5919	5596	4611
	LOG(PRE/OBS)			-0.24	-0.31	0.27	-0.23	-0.1	-0.43
DAY 4	T. TIME (hr)			0.23	4.18	6.97	11.4	13.11	17.45
CHLORINE-ON	OBSERVED	8300	270000	28000	10300	8400	9400	12700	11200
	PREDICTED			9028	9004	8859	8205	7875	6831
	LOG(PRE/OBS)			-0.49	-0.06	0.42	-0.06	-0.21	-0.21
DAY 5	T. TIME (hr)			0.24	4.26	7.1	11.38	13.77	16.25
CHLORINE-OFF	OBSERVED	7700	251000	84000	7100	9700	6800	10300	92000
	PREDICTED			8472	8448	8306	7656	7329	6301
	LOG(PRE/OBS)			-1	0.08	-0.07	0.05	-0.15	-1.16
DAY 6	T. TIME (hr)			0.23	4.13	6.88	11.13	12.76	15.06
CHLORINE-OFF	OBSERVED	143000	190000	14600	6400	8600	4400	6600	3800
	PREDICTED			142386	142001	139716	129460	124274	107885
	LOG(PRE/OBS)			0.99	1.35	1.21	1.47	1.27	1.45

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

Table 5 CONTINUED ....
COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR GRAND RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS							
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8
FALL									
DAY1 CHLORINE-ON	T. TIME (hr)			0.12	4.22	4.8	7.35	9.95	12.02
	OBSERVED	1100	190	580	800	640	620	370	510
	PREDICTED			1077	1061	1044	888	824	764
	LOG(PRE/OBS)			0.27	0.12	0.21	0.16	0.35	0.18
DAY 2 CHLORINE-ON	T. TIME (hr)			0.13	4.56	5.31	8.1	11.09	13.47
	OBSERVED	700	101000	2600	970	1500	600	400	640
	PREDICTED			755	742	729	609	559	511
	LOG(PRE/OBS)			-0.54	-0.12	-0.31	0.01	0.15	-0.1
DAY 3 CHLORINE-ON	T. TIME (hr)			0.13	4.61	5.35	8.19	11.21	13.62
	OBSERVED	860	1280	940	1400	1700	4100	1520	1110
	PREDICTED			841	827	812	679	623	659
	LOG(PRE/OBS)			-0.05	-0.2	-0.32	-0.78	-0.39	-0.29
DAY 4 CHLORINE-ON	T. TIME (hr)			0.13	4.55	5.27	8.02	10.95	13.27
	OBSERVED	1190	210000	1800	1130	900	1100	870	880
	PREDICTED			1313	1292	1269	1063	977	895
	LOG(PRE/OBS)			-0.14	0.06	0.15	-0.01	0.05	0.01
DAY 5 CHLORINE-OFF	T. TIME (hr)			0.13	4.56	5.32	8.11	11.1	13.48
	OBSERVED	2800	201000	9100	900	2100	1200	1700	740
	PREDICTED			2884	2839	2790	2342	2154	1974
	LOG(PRE/OBS)			-0.5	0.5	0.12	0.29	-0.1	0.43
DAY 6 CHLORINE-OFF	T. TIME (hr)			0.13	4.46	5.14	7.82	10.65	12.9
	OBSERVED	620	110000	7000	400	450	1500	1200	530
	PREDICTED			688	677	666	563	520	479
	LOG(PRE/OBS)			-1.01	0.23	0.17	-0.43	-0.36	-0.04

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG(PREDICTED/OBSERVED)

TABLE 6
SUMMARY OF PREDICTED TRAVEL TIMES WHERE BACTERIAL OBJECTIVES ARE MET - GRAND RIVER

Season & Date	Case	Travel Time (hrs) Where FC Objective = 100/100 mL		Travel Time (hrs) Where TC Objective = 1000/100 mL		Upstream River Discharge (m^3/s)
		Without Background	With Background	Without Background	With Background	
Summer						
August 4-6, 1979	Cl_2-ON:					
	Day 1	0.0	29.1	0.0	59.7	0.5667
	Day 2	0.0	25.51	0.0	59.9	0.5306
	Day 3	0.0	0.0	0.0	44.6	0.4697
Aug. 12-14, 1979	Cl_2-OFF:					
	Day 1	21.2	50.5	0.0	49.9	0.7398
	Day 2	28.38	48.6	0.0	48.5	0.6817
	Day 3	29.11	44.7	0.0	112.3	0.7449
Fall						
Nov. 5-7, 1979	Cl_2-ON:					
	Day 1	0.0	0.0	0.0	3.6	3.7575
	Day 2	0.0	0.0	0.0	0.0	3.0578
	Day 3	0.0	36.2	0.0	0.0	3.0573
Dec. 10-12, 1979	Cl_2-OFF:					
	Day 1	0.0	86.5	0.0	11.4	3.1377
	Day 2	0.0	3.5	0.0	42.9	3.0477
	Day 3	0.0	17.12	0.0	0.0	3.3075

Table 7 COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR OTONABEE RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS						
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7
SUMMER								
DAY1	T. TIME (hr)			0.02	0.78	1.35	4.73	12.16
CHLORINE-ON	OBSERVED	80	7000	72	68	1	90	63
	PREDICTED			173	175	174	169	162
	LOG(PRE/OBS)			0.38	0.41	2.24	0.27	0.38
DAY 2	T. TIME (hr)			0.02	0.56	0.97	3.39	9.92
CHLORINE-ON	OBSERVED	250	3500	40	324	283	330	1080
	PREDICTED			335	327	323	310	268
	LOG(PRE/OBS)			0.92	0	0.06	-0.03	-0.61
DAY 3	T. TIME (hr)			0.03	1.04	1.79	6.29	14.58
CHLORINE-ON	OBSERVED	80	1700	97	99	101	90	76
	PREDICTED			119	116	115	110	95
	LOG(PRE/OBS)			0.09	0.07	0.06	0.09	0.1
DAY 4	T. TIME (hr)			0.02	0.58	1	3.5	10.12
CHLORINE-ON	OBSERVED	100	340000	8820	3490	2350	761	521
	PREDICTED			7860	7679	7590	7310	6365
	LOG(PRE/OBS)			-0.05	0.34	0.51	0.98	1.09
DAY 5	T. TIME (hr)			0.03	0.94	1.63	5.71	13.71
CHLORINE-OFF	OBSERVED	108	77000	3430	5510	4900	11600	4680
	PREDICTED			2033	1985	1961	1886	1633
	LOG(PRE/OBS)			-0.23	-0.44	-0.4	-0.79	-0.46
DAY 6	T. TIME (hr)			0.03	1.06	1.87	6.5	
CHLORINE-OFF	OBSERVED	156	260000	17300	9040	5290	9180	5040
	PREDICTED			5755	5624	5559	5357	
	LOG(PRE/OBS)			-0.48	-0.21	0.02	-0.23	

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG (PREDICTED/OBSERVED)

TABLE 7 CONTINUED ....

COMPARISON OF OBSERVED AND PREDICTED FECAL COLIFORM DENSITIES (COUNTS/100 mL) FOR OTONABEE RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS						
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7
FALL								
DAY1	T. TIME (hr)			0.02	0.57	3.45	10.03	14.04
CHLORINE-ON	OBSERVED	110	200	106	103	65	56	41
	PREDICTED			111	109	107	104	91
	LOG(PRE/OBS)			0.02	0.02	0.22	0.27	0.35
DAY 2	T. TIME (hr)			0.02	0.62	3.78	10.53	14.76
CHLORINE-ON	OBSERVED	128	152	187	494	58	84	49
	PREDICTED			128	125	124	120	105
	LOG(PRE/OBS)			-0.16	-0.59	0.33	0.15	0.33
DAY 3	T. TIME (hr)			0.02	0.62	3.73	10.52	14.62
CHLORINE-ON	OBSERVED	48	50	64	82	12	6	16
	PREDICTED			48	47	46	45	40
	LOG(PRE/OBS)			-0.12	-0.24	0.58	0.88	0.4
DAY 4	T. TIME (hr)			0.02	0.5	3.01	9.25	13.05
CHLORINE-ON	OBSERVED	36	17200	165	529	454	652	971
	PREDICTED			1848	1819	1805	1759	1600
	LOG(PRE/OBS)			1.05	0.54	0.6	0.43	0.22
DAY 5	T. TIME (hr)			0.01	0.49	2.97	9.2	12.98
CHLORINE-OFF	OBSERVED	28	45000	4460	784	1210	890	1410
	PREDICTED			494	487	483	471	429
	LOG(PRE/OBS)			-0.96	-0.21	-0.4	-0.28	-0.52
DAY 6	T. TIME (hr)			0.02	0.54	3.25	9.69	13.58
CHLORINE-OFF	OBSERVED	32	29000	11100	1070	813	952	1060
	PREDICTED			369	364	361	353	323
	LOG(PRE/OBS)			-1.48	-0.47	-0.35	-0.43	-0.52

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG (PREDICTED/OBSERVED)

TABLE 8 COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR OTONABEE REIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS						
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7
SUMMER								
DAY1	T. TIME (hr)			0.02	0.78	1.35	4.73	12.16
CHLORINE-ON	OBSERVED	2000	30000	477	956	1010	2370	2380
	PREDICTED			2392	2349	2328	2262	2034
	LOG(PRE/OBS)			0.7	0.39	0.36	-0.02	-0.07
DAY 2	T. TIME (hr)			0.02	0.56	0.97	3.39	9.92
CHLORINE-ON	OBSERVED	1830	16000	612	1270	863	2605	2176
	PREDICTED			2196	2143	2116	2033	1755
	LOG(PRE/OBS)			0.55	0.23	0.39	-0.11	-0.09
DAY 3	T. TIME (hr)			0.03	1.04	1.79	6.29	14.58
CHLORINE-ON	OBSERVED	3000	6700	1510	1350	1390	1200	1292
	PREDICTED			3075	2999	2962	2846	2455
	LOG(PRE/OBS)			0.31	0.35	0.33	0.38	0.28
DAY 4	T. TIME (hr)			0.02	0.58	1	3.5	10.12
CHLORINE-ON	OBSERVED	2700	1300000	27100	11700	6520	5840	4370
	PREDICTED			32308	31563	31996	30047	26163
	LOG(PRE/OBS)			0.08	0.43	0.69	0.71	0.78
DAY 5	T. TIME (hr)			0.03	0.94	1.63	5.71	13.71
CHLORINE-OFF	OBSERVED	850	430000	11700	28900	20900	28000	14720
	PREDICTED			11712	11430	11291	10857	9395
	LOG(PRE/OBS)			0	-0.4	-0.27	-0.41	-0.2
DAY 6	T. TIME (hr)			0.03	1.06	1.87	6.56	15
CHLORINE-OFF	OBSERVED	500	1450000	109000	37900	20900	35300	19780
	PREDICTED			31732	31010	30653	29538	25762
	LOG(PRE/OBS)			-0.54	-0.09	0.17	-0.08	0.11

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG (PREDICTED/OBSERVED)

TABLE 8 CONTINUED ...
COMPARISON OF OBSERVED AND PREDICTED TOTAL COLIFORM DENSITIES (COUNTS/100 mL) FOR OTONABEE RIVER

STUDY PERIOD AND CONDITION	PARAMETERS	MONITORING STATIONS						
		Background	EFFLUENT	Station 3	Station 4	Station 5	Station 6	Station 7
FALL								
DAY1	T. TIME (hr)			0.02	0.57	3.45	10.03	14.04
CHLORINE-ON	OBSERVED	1100	600	633	438	615	534	340
	PREDICTED			1088	1065	1054	1018	896
	LOG(PRE/OBS)			0.24	0.39	0.23	0.28	0.42
DAY 2	T. TIME (hr)			0.02	0.62	3.78	10.53	14.76
CHLORINE-ON	OBSERVED	410	820	4720	870	1570	8640	1639
	PREDICTED			414	405	401	388	341
	LOG(PRE/OBS)			-1.06	-0.33	-0.59	-1.35	-0.68
DAY 3	T. TIME (hr)			0.02	0.62	3.73	10.52	14.62
CHLORINE-ON	OBSERVED	176	160	376	146	1340	400	303
	PREDICTED			175	172	170	164	145
	LOG(PRE/OBS)			-0.33	0.07	-0.9	-0.39	-0.32
DAY 4	T. TIME (hr)			0.02	0.5	3.01	9.26	13.05
CHLORINE-ON	OBSERVED	1010	130000	4378	5102	4068	4920	5616
	PREDICTED			2366	2329	2310	2252	2049
	LOG(PRE/OBS)			-0.27	-0.34	-0.25	-0.34	-0.44
DAY 5	T. TIME (hr)			0.01	0.49	2.97	9.2	12.98
CHLORINE-OFF	OBSERVED	1550	350000	31700	4150	4860	5781	9204
	PREDICTED			5160	5080	5040	4915	4478
	LOG(PRE/OBS)			-0.79	0.09	0.02	-0.71	-0.31
DAY 6	T. TIME (hr)			0.02	0.54	3.25	9.69	13.58
CHLORINE-OFF	OBSERVED	1330	186000	48400	5310	4720	6888	7332
	PREDICTED			3099	3053	3031	2960	2709
	LOG(PRE/OBS)			-1.19	-0.24	-0.19	-0.37	-0.43

NOTES : T. TIME = TRAVEL TIME
LOG(PRE/OBS) = LOG (PREDICTED/OBSERVED)

The plug flow model predictions of travel times at which the FC and TC densities are reduced to the guideline values have been summarized in Table 9. The trends of these travel times are generally similar to those of the Thames and Grand River values.

2.6 Sensitivity of Background Bacterial Densities

The model predictions for various river sites, presented in the previous section, indicated the significance of the background levels on the times of travel at which the water quality objectives are met. The analyses of each site were both without and with background bacterial densities. In order to further evaluate the sensitivity of the background levels, additional plug flow modelling studies were carried out for the Grand River site by assuming the following levels for the summer runs:

Background FC = 100/100 mL
Background TC = 1000/100 mL

These background levels are the same as the provincial water quality objectives (PWQO). The effluent densities, decay rates and other input parameters for the model were the same as those observed during the summer 1979 Cl_2-ON (August 4 - 6) and Cl_2-OFF (August 12 - 14) studies.

The predicted travel times below the outfall at which the FC and TC bacterial objectives can be met, are summaried in Table 10. A comparison of these travel times with the corresponding values (predicted with the observed background levels) in Table 6 indicates that the maintenance of background levels at or lower than the PWQO will result in significant reductions in the travel times (particularly for the disinfected case) within which PWQO cannot be met. These sensitivity run predictions indicate that efforts should be directed at maintaining background bacterial densities at or below the PWQO levels.

TABLE 9
SUMMARY OF PREDICTED TRAVEL TIMES WHERE BACTERIAL OBJECTIVES ARE MET - OTONABEE RIVER

Season & Date	Case	Travel Time (hrs) Where FC Objective = 100/100 mL		Travel Time (hrs) Where TC Objective = 1000/100 mL		Upstream River Discharge (m^3/s)
		Without Background	With Background	Without Background	With Background	
Summer						
June 5-7, 1980	Cl_2-ON:					
	Day 1	0.0	14.6	0.0	22.0	37.90
	Day 2	0.0	30.9	0.0	20.2	21.20
	Day 3	0.0	4.6	0.0	28.7	21.10
June 16-18, 1980	Cl_2-OFF:					
	Day 1	112.6	112.9	87.8	90.0	23.00
	Day 2	78.9	80.3	63.7	65.6	20.30
	Day 3	104.1	104.9	89.1	89.5	23.50
Fall						
Sept. 30 - Oct. 2, 1980	Cl_2-ON:					
	Day 1	0.0	3.0	0.0	2.5	34.10
	Day 2	0.0	7.0	0.0	0.0	34.50
	Day 3	0.0	0.0	0.0	0.0	39.00
Dec. 10-12, 1979	Cl_2-OFF:					
	Day 1	92.2	92.8	10.1	27.5	46.80
	Day 2	50.0	51.8	41.8	53.2	46.60
	Day 3	33.4	42.62	19.0	36.9	50.40

TABLE 10
SENSITIVITY OF BACKGROUND LEVELS ON PREDICTED TRAVEL TIMES - GRAND RIVER

Season & Date	Case	Travel Time (hrs) Where Objectives Are Met	
		With FC Background = 100/100 mL	With TC Background = 1000/100 mL
Summer			
August 4-6, 1979	Cl_2-ON:		
	Day 1	0.03	0.08
	Day 2	0.0	0.0
	Day 3	0.0	0.0
August 12-14, 1979	Cl_2-OFF:		
	Day 1	28.6	13.3
	Day 2	34.0	13.8
	Day 3	34.6	9.6

2.7 Discussion

The discrepancies between the observations and predictions could be due to various factors outlined earlier. These include field sampling methodology, imprecise analytical measurement techniques, effects of ambient environmental factors, etc. Attempts were made to qualitatively assess the possible effects of sediment characteristics, hydraulic parameters and inorganic water quality parameters on the modelling results by utilizing the data presented in the BEAK report. An examination of the pertinent data for the successive reaches from each river site did not reveal any clearly identifiable factors to explain the discrepancies. However, the empirical method of using an error range (defined by the ratio RL $\leq \pm$ 0.5) appears to accounts for these undefinable factors.

The plug flow model predictions were found to be reasonably comparable to the observations with very few exceptions for each site, as indicated by the acceptable values of RL. Thus, the assumed decay rates for FC and TC are reasonably satisfactory. Since all the river sites consist of fairly shallow reaches, the assumed decay rate appear to be valid for the river reaches studied herein. It is possible that these decay rates are valid for other shallow river reaches. These rates could be used for preliminary planning studies. However, their validity to a given site should be checked with the aid of field data and modelling studies.

3.0 STATISTICAL ANALYSIS

The total coliform (TC) and fecal coliform (FC) density data were correlated with Pseudomonas aeruginosa (PA) and Klebsiella (K). In the Beak report, the log (TC) and log (FC) were correlated with the log (PA) and log (K); however, the correlations were statistically not significant. These statistical correlations were repeated but the data were separated into groups for the river sites, namely, the Grand, Thames and Otonabee Rivers. The statistical results are summarized in Table 11. For the Otonabee River, K with TC greater than 1000/100 mL and K with FRC greater than 100/100 mL have correlation coefficients of 0.78 and 0.79, respectively. The correlation coefficients are not statistically significant for all other cases.

To determine whether better statistical correlations could be obtained, the data sets were partitioned. There is a low value bias of 4 counts/100 mL for PA in the data sets; consequently, a new data set was created, omitting all PA densities of 4 or less. It is also known that the FC density evaluation is imprecise. Data from the Eastern Beaches (Toronto waterfront) indicated a precision of log (var) equal to 0.54 and the MOE data have indicated a precision of log (var) equal to 0.7 for Lake Ontario (Gore & Storrie Limited, 1985). Furthermore, the present guidelines for FC for receiving waters are that the geometric mean of 10 samples should not exceed 100/100 mL. The following table shows the upper limits for the FC geometric mean of 100/100 mL based on sample size, assuming a normally distributed population (U.S. Federal Register 49 (102); 21987, 24 May, 1984):

No. of Samples	Log (Var) = 0.54	Log (Var) = 0.7
1	778	1429
2	427	655
5	250	329
10	191	232

TABLE 11

	Total Coliforms (Counts/100 mL) 100 to 1000	Total Coliforms (Counts/100 mL) 1001 to 10000	Fecal Coliforms (Counts/100 mL) 10 to 100	Fecal Coliforms (Counts/100 mL) 101 to 1000
PSEUDOMONAS AERUGINOSA				
Grand River				
Number of Readings	21	41	25	57
Intercept	0.63	- 1.60	0.55	- 0.19
Slope	- 0.0056	0.72	0.18	0.42
Correlation Coefficient	- 0.0042	0.40	0.08	0.25
Thames River				
Number of Readings	2	57	2	81
Intercept	-	1.79	-	- 0.02
Slope	-	- 0.21	-	0.37
Correlation Coefficient	-	- 0.14	-	0.19
Otonabee River				
Number of Readings	17	64	28	44
Intercept	- 0.74	- 1.18	0.60	- 0.15
Slope	0.38	0.45	- 0.20	0.21
Correlation Coefficient	0.20	0.40	- 0.15	0.24
KLEBSIELLA				
Grand River				
Number of Readings	30	52	32	64
Intercept	1.62	2.95	1.81	2.35
Slope	0.20	- 0.23	0.14	- 0.10
Correlation Coefficient	0.11	- 0.21	0.11	- 0.09
Thames River				
Number of Readings	5	61	5	89
Intercept	2.15	2.40	0.28	1.01
Slope	0.12	0.01	1.03	0.51
Correlation Coefficient	0.04	0.01	0.54	0.27
Otonabee River				
Number of Readings	20	44	33	26
Intercept	0.40	- 3.48	1.11	- 0.33
Slope	0.47	0.61	0.32	0.99
Correlation Coefficient	0.29	0.78	0.20	0.79

Slope assumes TC/FC are independent variables.
Correlation coefficient assumes both TC/FC and PA/K are dependent variables.

The bacteriological sampling in the BEAK study involved one sample at each station. Therefore, instead of the interval 10 to 100/100 mL and 101 to 1000/100 mL for FRC densities, the intervals of 0 to 777/100 mL and 778 to 7000/100 mL were used assuming a precision of log (var) = 0.54. The results of the statistical fitting of this data set are presented in Table 12. This partitioning of the data set did not improve the statistical fitting for the Grand and Thames Rivers, however, it did produce statistically significant relationships for PA/FC for the Otonabee River data.

Tables 11 and 12 shows that the correlations between TC/FC with PA/K are generally statistically not significant for the data sets, except for the Otonabee River data which has the following relationships:

Otonobee River		
1.	TC = 1001 to 10,000/100 mL	log (K) = 3.48 = 0.6 log (TC)
2.	FC = 10 to 777/100 mL	log (PA)= 1.34 - 0.2 log (FC) log (K) = 0.68 + 0.57 log (FC)
3.	FC = 778 to 7000/100 mL	log (PA)= - 1.45 - 0.74 log (FC) log (K) = 0.19 + 0.82 log (FC)

TABLE 12

	Fecal Coliforms	
	10 to 777	778 to 7000
GRAND RIVER		
Pseudomonas aeruginosa		
Number of Readings	24	16
Intercept	1.05	1.78
Slope	0.19	- 0.13
Correlation Coefficient	0.17	- 0.09
Klebsiella		
Number of Readings	86	29
Intercept	1.98	- 1.05
Slope	0.05	1.05
Correlation Coefficient	0.05	0.63
THAMES RIVER		
Pseudomonas aeruginosa		
Number of Readings	49	56
Intercept	0.78	- 0.19
Slope	0.11	0.48
Correlation Coefficient	0.08	0.28
Klebsiella		
Number of Readings	77	67
Intercept	1.06	2.17
Slope	0.48	0.11
Correlation Coefficient	0.37	0.06
OTONABEE RIVER		
Pseudomonas aeruginosa		
Number of Readings	7	25
Intercept	1.34	- 1.45
Slope	- 0.20	0.74
Correlation Coefficient	- 0.87	0.83
Klebsiella		
Number of Readings	54	16
Intercept	0.68	0.19
Slope	0.57	0.82
Correlation Coefficient	0.56	0.88

4.0 SUMMARY AND CONCLUSIONS

Data related to bacteriological impact of effluent discharges to water bodies were analyzed. The studies were conducted by BEAK Consultants Limited during 1979-82 at the following sites:

- Thames River - Ingersoll WPCP
- Grand River - Grand Valley WPCP
- Otonabee River - Peterborough WPCP
- Lake Ontario at Port Hope WPCP

The data review and analyses focussed on the following objectives:

1. Determination of longitudinal and lateral distances (or travel times) with respect to the WPCP outfalls at which the fecal and total coliform densities are reduced to 100/100 mL and 1000/100 mL respectively, for both chlorine disinfection and no-disinfection periods.

2. Establishment of probabilistic distributions of pathogenic bacteria concentrations in receiving streams when:

   (a) Total coliform concentrations in the same water were between 100 to 1000/100 mL or fecal coliform concentrations were between 10 to 100/100 mL; and
   (b) Total coliform concentrations were between 1000 to 10,000/100 mL.

The suitability of data presented in the BEAK report for applying the state-of-the-art models to each site was evaluated. It was found that 2-D models (capable of simulating transport due to lateral dispersion, longitudinal convection and decay) could not be utilized because of limitations in the data. Also, the lake study data was found to have large fluctuations and/or insufficient information for modelling purposes, and hence, the lake study data were not analyzed.

The plug flow model was determined to be the most suitable model for the three river site analyses. The model was applied for each day of sampling, since the effluent and background loadings were different on each day. The bacterial decay rate was assumed to be 1.0/day (20° C, base e) for both TC and FC.

The predictions of the plug flow model were in reasonable agreement with the observations in most cases, the differences lying within one-half log cycle. The discrepancies between the observed and predicted values were found to be particularly pronounced for the sampling days on which the background levels differed significantly from the other days' values and at the first station below the outfall. This was the case for each site. Generally, the travel times at which the TC and FC densities are reduced to the guideline limits (stated in the first objective) have been found to be lower for the case of effluent disinfection at each site compared with the non-disinfected effluent discharge cases. A sensitivity analysis showed that the background densities of FC and TC could significantly affect the travel times where the objectives can be met.

Statistical correlation analyses of pathogen and indicator bacterial densities were carried out. No correlation relationships could be found for the Thames and Grand River data. Only the Otonabee River bacterial data showed correlations between: (a) *Klebsiella* and TC; (b) *P.aeruginosa* and FC; and (c) *Klebsiella* and FC. These relationships are established for the ranges TC = 1001 to 10,000/100 mL, FC = 10 to 777/100 mL and FC = 778 to 7000/100 mL in order to account for imprecise evaluations of the bacterial densities.

REFERENCES

Beak Consultants Ltd., 1982. Bacteria in Sewage Effluents - The Effects of Hydraulic Characteristics and Effluent Chlorination on the Incidence of Micro-Organisms of Public Health Significance in Receiving Waters. Technical report prepared for the Ministry of the Environment, Toronto, Ontario.

Gore & Storrie Limited, 1984. Ottawa River Nuclear Spill Contingency Model Development. Technical Report prepared for the Ontario Ministry of the Environment, Toronto.

Gore & Storrie Limited, 1985. Eastern Beach Study - 1984. Technical report prepared for the City of Toronto.

Gowda, T.P.H., 1980. Stream Tube Model for Water Quality Predictin in Mixing Zones of Shallow Rivers. Water Resources Paper 14, Water Resources Branch, Ministry of the Environment, Toronto, Ontario, Canada. 141 pp.

Gowda, T.P.H., 1984a. Critical Point Method for Mixing Zones in Rivers. J. Environmental Engineering, Amer. Soc. Civ. Eng. 110 (1): 244-262.

Gowda, T.P.H., 1984b. Water Quality Prediction in Mixing Zones of Rivers. J. Environmental Engineering, Amer. Soc. Civ. Eng. 110 (4): 751-769.

Gowda, T.P.H. and Post, L.E., 1984. Mixing Zone Studies in the Grand River Basin. Canadian Journal of Civil Engineering 11 (2): 204-216.

Hamdy, Y., 1981. Dispersion of Effluent Plumes from Diffusers on Near-Shore Regions of the Great Lakes. Vol. 1 - Initial Mixing Processes. Great Lakes Section, Water Resources Branch, Ministry of the Enviroment, Toronto.

Kohli, B., 1981. Dispersion of Effluent Plumes from Diffusers on Near-Shore Regions of the Great Lakes. Vol. II - Surface Silution. Great Lakes Section, Water Resources Branch, Ministry of the Environment, Toronto.

Post, L.E. and Gowda, T.P.H., 1981. Effluent Mixing Zone Studies. Grand River Basin Water Management Study - Technical Report No. 29, Water Resources Branch, Ontario Ministry of the Environment, Toronto.

Putz, G., et al, 1984. Micro-organism Survival in an Ice-Covered River. Canadian Journal of Civil Engineering 11 (2): 177-186.

Smith, D.W., et al, 1983. Effluent Mixing in Northern Rivers - The Bank Discharge. paper presented at the Chemical Institute of Canada Conference, Calgary, June 1983.

Zison, S.W., et al, 1978. Rates, Constants and Kinetic Formulations in Surface Water Quality Modelling. Tetra Tech., Inc., Lafayette, California. Technical report prepared for the U.S.E.P.A. 317 pp.

APPENDIX

EXECUTIVE SUMMARY

Chlorine disinfection of water has been a standard and widely accepted practice since it was first introduced at the turn of the century. This method of treatment has thrived over the years, having proven remarkably effective in controlling waterborne bacterial diseases. Recently, the chlorine disinfection process has come under increased scrutiny as environmental side effects of chlorinated compounds are drawing the attention of the scientific community.

The process of chlorination of sewage plant effluents has been widely adopted for the destruction of residual pathogenic micro-organisms. The two most common forms of this treatment involve the continuous addition of either hypochlorite (sodium or calcium) or chlorine gas to the effluent. The chlorine disinfection process results in the conversion of the higher oxidation state chlorines to chlorides. Disinfection of domestic waste treatment effluent is often considered adequate when a combined available residual of 0.5 mg L^{-1} is achieved after 15 minutes of contact.

The International Joint Commission has recently proposed a residual chlorine water quality objective which would require many Ontario treatment plants to dechlorinate effluents or employ alternative forms of disinfection. At considerable cost, effluents could be rendered non-toxic to aquatic life by eliminating chlorine residuals. However, chlorinated organic compounds or, alternatively, ozonated compounds could still pose an environmental health problem. Clearly, the preferred solution would be to not disinfect at all, or at certain times, if the die-off of pathogenic bacteria could be left to natural conditions with assurance that public health would not be jeopardized.

In June 1979, the Ontario Ministry of the Environment (MOE) selected Beak Consultants Limited (BEAK) to carry out a study supported by the Provincial Lottery Fund to investigation hydraulic, water quality, and atmospheric conditions which contribute to the die-off of bacteria from chlorinated and non-chlorinated sewage effluents in receiving waters.

In order to assess the advantages and disadvantages of sewage chlorination, it was necessary to address several factors. The objectives of the study were:

1. To determine the incidence of pathogenic bacteria and indicator bacteria in sewage treatment plant effluents and their receiving waters, both with sewage chlorination and without;

2. To determine if, in these waters, chlorination results in a significantly lower concentration of pathogenic bacteria than in the case of non-chlorinated effluents;

3. To investigate those hydraulic, water quality, and atmospheric conditions which may contribute to the natural die-off of pathogenic bacteria in non-chlorinated effluents and their receiving waters.

4. To determine the need and desirability for using selected pathogenic bacteria in place of indicator organisms as a measure of conditions hazardous to public health in effluents and receiving waters in Ontario, particularly where and when effluents are not chlorinated.

A study plan was set up based on a three-phase, three-year approach. Year 1 involved two plants discharging to riverine environments; year 2 included one plants with riverine and one plant with lacustrine receiving waters; year 3 comprised co-ordination studies, data interpretation, and final report submission.

The program was designed to encompass these concerns and this timetable addressed itself to several critical elements in the investigation.

Bacteriological analyses were conducted on-site in a mobile field laboratory. This permitted analyses to commence within one to four hours of the time of sample collection, regardless of sampling location.

Methodology was carefully reviewed with the Liaison Committee before the program was initiated, as well as throughout the field period. Investigation of media suitability, recovery and confirmation of colonies was carried out routinely to establish quality control.

Rigorous quality assurance studies were carried out with the MOE Taxonomy Section participating as the external reference laboratory.

The study approach was to measure as many factors as possible that influence bacterial growth and mortality, simultaneously with the bacterial monitoring of receiving waters. The factors considered were:

1. Hydraulic Characteristics of the receiving water, including time of travel, velocities, and cross-sectional profiling;

2. Water quality characteristics including any waterborne chemical parameters which might be involved in interactions with biological organisms that could influence the propagation or die-off of these bacterial organisms;

3. Characteristics of the in-stream sediments which could affect bacterial regrowth including sediment bacteria, macro-organisms and sediment classification;

4. Meteorological factors influencing growth and die-off which include solar radiation, temperature, precipitation. The lake study was also greatly affected by wind speed and direction.

Site Selection

At the begining of each study year, a selection of treatment plants was made, based on the requirements of the study, availability of plant and ability to undergo periods of non-chlorination without endangering public health. In meetings between BEAK project personnel and the MOE Liaison Committee, Grand Valley on the Grand River and Ingersoll on the Thames River were selected for investigation during the first year. In the year, Peterborough on the Otonabee River and Port Hope on Lake Ontario were chosen for study.

River Based Studies

GRAND VALLEY

MOE operates an extended aeration treatment plant for the town of Grand Valley. The facility is situated at the south end of the town and discharges to the Grand River via a sewer and a single outfall located on the west bank of the river. The effluent and receiving water are soon mixed, passing over a series of short pools and riffles for the first 0.5 km. There are no major tributaries or effluent sources between Grand Valley STP and Belwood. Station locations o the Grand River were determined based on the approximate time of travel at that time of year. Stations for chlorination and non-chlorination for each survey were the same.

INGERSOLL

Sewage from the town of Ingersoll is treated in a conventional secondary treatment facility operated by the Ontario Ministry of the Environment. The final treated effluent leaves the chlorination contact chambers and is discharged at the north shore of the Thames River downstream of Ingersoll via two outfalls, one from the new plant and one from the old plant, both open culverts with an armoured skirt to prevent erosion. The sampling periods were carried out at Ingersoll during September and December 1979, and February 1980. The stations extended westward from Ingersoll approximately 6 km and 12-18 hours time of travel.

PETERBOROUGH

The Peterborough water pollution control plant is located on the east bank of the Otonabee River in the city's east side approximately 1.6 km downstream of Lock 19 of the Trent Canal System.

The facility is composed of two conventional secondary plants, one old and one new, which operate in parallel before discharging to a shared chlorine contact chamber operated on a liquid chlorine supply. Sewage effluent is chlorinated only between 15 May and 31 October.

The Peterborough STP treats an average 12 MIGD of sewage before discharge to the Otonabee River (1976 data). Sampling was undertaken during June and October 1980 on the Otonabee River and was carried out between the plant and Squirrel Creek, covering a zone of up to 10-16 hours time of travel.

Study Outline

Eight stations were established for the river-based plants: a control above the outfall, the outfall stream and six downstream of the outfall, spanning a period of up to 12-18 hours time of travel after release to the receiving waters.

Surveys were carried out on a seasonal basis, based on a three-consecutive-day sampling during routine chlorination, followed by a 7-10 day stabilization period during which no chlorination was carried out at the plant. This stabilization period was followed by a second three-day sampling period at the termination of which, chlorination was re-commenced.

Each three-day sampling period was comprised of a regular daily sampling at each station. Extra samples were taken on the first day of each three-day period to assess diurnal fluctuations in the background, effluent and mixing zone.

At Peterborough, cross-sectional sampling was carried out to assess lateral variation of bacterial and chemical concentrations.

Detailed chemical and micro-biological analysis was carried out for the following parameters:

Bacterial Parameters

Total coliform	(TC)
Fecal coliform	(FC)
Fecal streptococcus	(FS)
Pseudomonas aeruginosa	(PS)
Klebsiella	(KB)

Chemical Parameters

Temperature	Nitrite
Dissolved Oxygen	Ammonia
pH	Total Kjeldahl
Chlorine	Nitrogen
Conductivity	Total Phosphate
Turbidity	Suspended Solids
Nitrate	BOD (nitrification inhibited)

In order to relate these to physical (hydraulic) parameters, streamflow data was obtained from the Water Survey of Canada in Guelph and used in conjunction with time of travel determinations, made by monitoring the passage of a conservative tracer substance down the river. Meteorological parameters were measured by a six parameter met. station installed on site at the STP under investigation.

In addition, the mixing zone of the effluent was determined using a continuous low-level tracer injection and monitoring, as well as the cross-sectional area and cross-sectional velocities. This data was used to evaluate the extent of mixing in the effluent plume and to obtain a comparable concentration with other stations downstream of the mixing point.

Lake Based Studies

PORT HOPE

The Port Hope STP is located at the east end of Lake Street on the eastern edge of the town of Port Hope between Lake Ontario and the main railway lines. The effluent from both the old and new plants is chlorinated in a single 41 100 IG contact chamber operated on chlorine gas and having a retention time of 29.6 minutes at 2 MIGD load (1976). The effluent from the contact chamber is gravity-fed through a 60 cm diameter 350 m long outfall sewer (capacity 5.75 MIGD) to a T-shaped diffuser approximately 250 m out in Lake Ontario, 2 - 2.5 m beneath the surface.

Study Outline

Eight stations were established within the plume. The stations were arranged to provide cross-plume samples and encompassed up to 8 hours total time of travel from the chlorine contact chamber. Surveys were carried out during July and September 1980 based on the same samping schedule as outlined for rivers. Regular and intensive sampling was carried out concurrently with plume tracing. A conservative dye tracer was used to monitor the progress of the plume from release at the diffuser.

The intensity of sampling and analysis was identical to that previously outlined for the river-based plants. All parameters for water and sediment were the same; the hydraulic study was necessarily modified to allow evaluation of the unbounded discharge conditions present at Port Hope which result in a three dimensional multi-directional plume that has a variable mixing zone.

Results

The study was designed primarily as a collection of data involving a wide range of parameters. A preliminary analysis of this data was undertaken in order to respond to the four concerns outlined as objectives at the start of the study.

BEAK has undertaken a novel approach to assessing bacterial kinetics. Rather than utilize the traditional method of comparing analytical concentrations of bacteria, BEAK has instituted a new technique of determining bacterial mass. This mass term integrates the bacterial concentrations and hydraulic flows to produce an average mass of bacteria at a given point. This point, in the cases considered here, is actually a cross-section of the river. The total number of colonies passing through this cross-section in a given time (one second) was determined. In this way, the data available at each measured location (cross-section) can be compared to other cross-sections. This approach overcomes the biasing effect of high concentrations, particularly in the mixing zone, which have hampered traditional kinetic studies.

The bulk of data obtained for the sewage treatment plants studied was condensed to three volumes containing some 80-100 summary figures, maps and graphs and 100-120 summary tables of chemical, micro-biological and hydraulic data.

Data from Port Hope revealed very low input from the plant due to significantly lower loading than expected. This, combined with high background readings from the surrounding area implied that a far more detailed analysis would be required to evaluate the data base.

Since the study was designed as primarily a collection of data with only preliminary analysis, efforts were concentrated on the river based studies at this time.

For all three river-based sites, an extensive data base was collected for chemical, bacteriological, hydraulic and meteorological analyses. In order to assess the extent of microbiological activity, the analytical results were corrected where possible to provide comparable data among stations. These corrections included cross-sectional averaging in the mixing zone based on sampling locations, measured depth and velocity distributions to account for lateral variations and backtracked to determine the release time from the outfall. At release times, corresponding to each downstream station, measured flows and concentrations for both river and effluent were used to calculate the average mixed conservative in-stream concentration. This data was compared to the measured downstream data at the observed times of travel to provide an estimate of individual decay for each station for each bacteria type. For each river survey, results from the bacteriological analysis were combined with the appropriate measured hydraulic data to provide a record of bacterial mass flow versus river time of travel.

This analysis, which explicitly considers the temporal behaviour of river flow and effluent discharge as well as the variation in both background and effluent bacterial concentrations, indicates a consistent trend in the data. At Grand Valley on the Grand River, the mass of bacteria added to the river with and without chlorination is a very small fraction of the bacterial mass present due to background

conditions. As a result any dynamic effects which may occur are masked by the natural variation in the data. For the data analyzed, with or without chlorination, the measured downstream bacterial mass in consistently at or below background levels.

For both Ingersoll on the Thames River and Peterborough on the Otonabee River, the additional mass added to the river during chlorination as a consequence of the effluent discharge is a larger percent of the endogenous or background bacterial mass. During periods of non-chlorination, the effluent discharge contributes significantly to the background mass such that the mean mass flow in the river below the outfall is raised, in some cases, by approximately an order of magnitude. Apparent decay in bacterial mass to background levels downstream of the outfall is observed to occur at rates ranging from very rapid to very slow or not at all. This high degree of variation may be due to the lack of statistical certainty in the measured downstream bacterial data or it may be due to site-specific characteristics. Further analysis is required before any conclusions can be drawn.

In an attempt to carry out a limited assessment of bacterial kinetics, the data sets corrected to give the best estimate of concentration were converted to mass flow figures in counts per second. For each three-day sub-survey geometric means and deviations were calculated for the effluent and background values from all recorded measurements. These means and standard deviations of the generated conservative concentrations were plotted as a range from Cij + S to Cij - S as mass flow both for background and for background plus effluent.

Comparisons were made between each pathogenic organism measured and each indicator organism for all of the samples obtained during the study periods.

For each station sample, salmonellae were analyzed for on a present or absent basis on one day of each three-day survey. At Peterborough two positives were recorded in the effluent and outfall area during the second non-chlorination study. At Port Hope, five positives were identified: one in the plant effluent during chlorination and four in

the influent, effluent and receiving waters during non-chlorination. Four positive results were detected in the Grand River during the chlorination-on period; all in the receiving water downstream of the outfall. Ten positives were found at Ingersoll, one in the receiving waters during chlorine-on and the remainder from effluent and downstream stations during periods of effluent non-chlorination.

TH/avf
20009-01C.1/MISA/MUN88-1.0